INFLUENCE OF CLASS C FLY ASH ON THE PROPERTIES OF CONCRETE

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CHAPTER I

SUMMARY AND CONCLUSIONS

The behavior of concrete mixes containing various amounts of a fly ash conforming to ASTM C 618, Class C, was investigated. Behavior was referenced to a mix which satisfied Oklahoma Department of Transportation (ODOT) specifications for a Class A mix. A Class A concrete contains six sacks of portland cement per cubic yard (335 kg/m^3) and is used for pavements and for general construction where very high strength and durability are not required. Twenty to fifty percent of the portland cement was replaced--on a weight basis--and the mix water and the air entraining agent (AEA) dosage were adjusted to keep the slump and air content within the limits specified for a Class A concrete.

Two areas of investigation, designated as task I and task II, were pursued simultaneously. In one task of the project, the durability of the various mixes was investigated using Procedure A of ASTM Test for Resistance of Concrete to Rapid Freezing and Thawing in Water (C 666-77). In the other task, the influence of ambient temperature was studied. In this work concrete was batched and mixed at 55, 70, or 90 F (13, 21, or 32 C); the influence of temperature on the quantities of mix water and AEA dosage and on the time of set was established. In this task the initial mixing was followed by a period of prolonged agitation; during this time, slump, temperature, and air content were monitored.

1.1 Influence of Fly Ash on Freeze-Thaw Durability

Three series of freeze-thaw tests were performed. Each series involved one batch of concrete without fly ash--the Class A mix--and four batches of fly ash concrete; the weight of fly ash in these batches was 20, 30, 40, or 50 percent of the weight of cement in the Class A mix. Three prisms from each batch of concrete were subjected to freeze-thaw action.

All concrete tested in this phase of the investigation exhibited very high resistance to the freeze-thaw action. Consequently, there was no indication that fly ash influenced the durability of concrete. After completion of the freeze-thaw tests, specimens were cut from the prisms and polished; an examination of the hardened air void system indicated that most concrete contained what is normally considered an acceptable entrained air system. Data related to the hardened air void system are somewhat subjective and were obtained by more than one microscopist; air void parameters were based on a computed rather than a measured paste content. For these reasons, the air void data exhibited rather large scatter; however, no correlation between the fly ash percentage and the resulting air void system was evident.

1.2 Influence of Fly Ash on Mix Proportions

In this study the total weight of cementitious material--portland cement plus fly ash--and the weights of the fine and coarse aggregates were held constant. Only the amount of mix water and AEA were varied to achieve a slump within the range of 1 to 3 in. (25 to 75 mm) and an air content between 5 and 7 percent. Based on data obtained during both the freeze-thaw and ambient temperature phases of the project, it was found that as the percentage of fly ash was increased, the mix water decreased while the quantity of AEA increased. Other research studies have also observed that a Class C fly ash can permit a reduction in mix water. However, the influence of fly ash on the quantity of AEA appears to be closely tied to the alkali content of both the portland cement and fly ash. In particular, the fly ash used in this study contained very small quantities of water soluble alkalies. Therefore, it is believed that findings in this investigation regarding air entrainment dosages are probably not applicable to other shipments of fly ash from the same or different sources.

1.3 Influence of Fly Ash on the Properties of Concrete

As the percentage of fly ash was increased, the time of set increased. A concrete with 50 percent fly ash replacement took approximately twice as long to set as a control mix without fly ash. However, this retarding action was not evidenced by concrete in the plastic condition; data obtained during extended agitation suggest that fly ash will slightly accelerate the stiffening of a concrete.

Fly ash did not significantly influence the loss in air content during agitation. As discussed above, the cement and fly ash used in this study contained unusually low amounts of alkalies; as a result, the influence of fly ash on air loss when concrete is made with materials having normal or above normal alkali contents was not established.

Mixes with 20 to 40 percent fly ash usually had higher compressive strength than concrete without fly ash. Data indicated the modulus of elasticity was dependent on the compressive strength of concrete. Any influence fly ash produced on the compressive strength resulted in a corresponding change in the modulus of elasticity.

CHAPTER II

INTRODUCTION

2.1 General

The use of pulverized coal as a fuel source to obtain electrical power is increasing yearly. Along with increased coal utilization is the increased production of waste by-products caused by the coal combustion process. A large percentage of the waste by-products is fly ash, which is the term for the finer ash collected from the plant gases before they are released into the atmosphere.

Fly ash has long been recognized for its pozzolanic activity when used as an admixture for concrete. A pozzolan is defined by the American Concrete Institute (1)* as:

> A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (p. 36).

This definition of a pozzolan is well suited for the fly ash produced from bituminous and anthracite coals. However, the western coals, such as lignite or subbituminous material, produce a high-lime fly ash that is not only pozzolanic but also somewhat cementitious.

The technology involving cement replacement with high-lime fly ash is still developing. As a result, most available literature is

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*Numbers in parentheses refer to entries in the list of References.

referenced to bituminous fly ash which, over a number of years, has been well documented as a suitable cement replacement.

With the utilization of western coals increasing, interest by road officials to use the growing quantities of western fly ash has also increased. Because portland cement is considerably more expensive than fly ash, partial replacement of cement with the waste by-product would help reduce paving costs. However, information regarding the characteristics of high-lime fly ash on concrete is limited, which indicates an area of research worthy of study.

2.2 Purpose and Scope

Two areas of investigation were pursued simultaneously and are designated as task I and task II. The purpose of task I was to determine if the addition of fly ash altered the freeze-thaw resistance of a concrete used for paving construction. The purpose of task II was to furnish information on the characteristics of fly ash concrete mixed under simulated field conditions. The Class C fly ash used in both tasks was produced from subbituminous Wyoming coal and replaced cement on a one-to-one weight basis.

In task I, freeze-thaw durability of an ODOT Class A concrete and four modified mixes were studied. Replacement percentages of the four modified mixes were 20, 30, 40, and 50 percent. Because of possible strength differences between the modified mixes and the control mix at the time of initial freeze-thaw testing at 14 days, sufficient samples from each batch were cast to allow durability tests on samples cured both 14 and 120 days. Three series, each consisting of the control mix and four modified mixes, were tested. The specimens were tested in accordance with Procedure A of ASTM Test for Resistance of Concrete to Rapid Freezing and Thawing (C 666-77).

Task II also used a Class A control mix and four modified mixes with cement replacements of 20, 30, 40, and 50 percent fly ash by weight. The control mix and four modified mixes were mixed at temperatures of 55, 70, and 90 F (13, 21, and 32 C). For each ash percentage, two batches were cast. One of the batches had an initial air content between 5 and 6 percent, while the other had an air content between 5 and 7 percent. The time of set was measured for each batch while concrete was maintained at the casting temperature. After the initial mixing period and at 30-minute intervals while the mixer operated at a reduced agitation speed, the slump, air content, and temperature were monitored.

CHAPTER III

BACKGROUND

In the following sections a brief background on the use of fly ash in concrete is presented. In Chapters V and VI additional information relevant to phases of this program is provided.

3.1 Historical Development

3.1.1 Natural Pozzolans

Hydraulic limes produced by calcining limestone with argillaceous impurities were used by the Greeks and Romans. Both also developed hydraulic motors involving finely ground volcanic ash, lime, and sand. The Romans used a volcanic tuff found near Pozzuoli, Italy. The term "pozzuoli" thus became associated with the siliceous material. From "pozzuoli" evolved the modern term "pozzolan."

Initial use of pozzuoli was restricted to unexposed construction, primarily because of unproven durability. Over 300 years passed before this hydraulic mortar was used for major architectural structures. However, the Pantheon, built largely of concrete, is evidence of the surprising durability ofthe Roman mortar (2).

During the Middle Ages, there was a decline in the quality of mortars; the art of burning lime was apparently lost. It was not until the fourteenth century that high quality mortars made with pozzolans reappeared. In 1756, John Smeaton, while preparing to build the Eddystone

Lighthouse, conducted tests which revealed that the best mortars were obtained using a limestone containing a high percent of clayey material (3).

In 1824, Joseph Aspin, a Leeds builder, obtained a patent for "portland" cement. However, temperatures in his kiln were not high enough to produce a clinker. The first cement comparable to the present portland cement was produced by Isaac Johnson in 1849 (3). With the abundance of materials necessary for the production of portland cement, the use of pozzolans mixed with lime as a means for making concrete declined rapidly.

With the initiation of reclamation programs and the development of hydroelectric power around 1910, there was renewed interest in pozzolans. Engineers used pozzolans to solve some of the problems associated with mass concrete construction. With mass concrete, there is an increase in temperature caused by the heat of hydration of the cement. Because the temperature rise occurs early before the concrete has gained full strength and rigidity, the thermal expansion usually can be accommodated without major distress. However, as the concrete cools, tensile stresses are developed which can cause severe cracking and serious structural damage. When a pozzolan is used as a cement replacement, the heat of hydration and associated temperature rise are greatly reduced. As an added benefit, pozzolans combine chemically with free lime which is produced during the hydration of portland cement to form a strong, nonleachable material. When pozzolans are used with portland cement, early strengths are usually low while later strengths are high. In addition, the pozzolanic reaction with lime is slow and requires the maintenance of moist curing for prolonged periods. As a result, most applications of portland-pozzolanic concrete have been in the area of mass concrete construction.

3.1.2 Fly Ash as a Pozzolan

Fly ash is a waste product of the coal combustion process. It is the term for finer ash collected from flue gases before they are released into the atmosphere. Since collected particles are difficult and in most instances costly to dispose of, efforts have been directed to turn the waste product into an asset. As a result, several marketable uses have been developed for fly ash. One such use was to take advantage of the pozzolanic properties of fly ash by combining it with portland cement, either as a cement replacement or as an admixture.

In the United States, one of the first recorded uses of fly ash with portland cement was in 1936 (4). Fly ash was used as an admixture in concrete placed in a retaining wall along Lake Michigan. Six years later the Bureau of Reclamation first used fly ash in the repair of the Hoover Dam spillway. The Bureau's next use of fly ash was in the construction of the Hungry Horse Dam where 261 million pounds (118 Gg) of fly ash were used. Fly ash was credited with reducing the construction time by one year and the cost by about 1.7 million dollars. Also constructed at about the same time by the Bureau was the Canyon Ferry Dam (5).

Following an intensive laboratory investigation of pozzolans in mass concrete, the Corps of Engineers used fly ash in the Sutton Dam on the Elk River in 1958 (6). Since then, four major agencies--the Bureau of Reclamation, the Corps of Engineers, the Hydro-Electric Power Commission of Ontario, and the Tennessee Valley Authority--have constructed several major structures using fly ash concrete (6).

In work reported by Larson (7), the Wisconsin Highway Commission placed 3.3 miles (5.3 Km) of concrete pavement under their supervision in 1949. Three concrete mixes containing type IA portland cement were studied. Two of the mixes contained fly ash. Cores taken from the pavement after three years did not reveal any detrimental influence from the presence of fly ash.

In Kansas, during the summer of 1949, 12 test sections of the McPherson Test Road, each 488 feet (149 m) long, were constructed using fly ash. Two other pozzolans were used in other test sections. Peyton et al. reported that the brand of cement was more important than the presence of a pozzolan. None of the pozzolans was as effective as limestone sweetening in reducing map cracking. However, fly ash was more effective than the other two pozzolans. Somewhat contradictory, Stingley and Peyton (9) later reported that when concrete contained fly ash, surface cracks were reduced and map cracking linked to available aggregate was eliminated. Abdun-nur (4) inspected the test road eight years after construction and found evidence of map cracking in most slabs. Concrete made with fly ash was generally in better condition than concrete made with other pozzolans and was definitely better than the control.

3.2 Chemical and Physical Properties of Fly Ash

Coal ash is a major waste product of the coal combustion process. The chemical composition of coal ash is dependent upon type and relative amount of minerals associated with the coal. The minerals usually consist of coal forming materials along with inorganic materials which may be added during the mining process or intentionally added to alter the characteristics of the ash. Coal is burned at furnace temperatures between 2500 and 3100 F (1400 and 1700 C) with coal ash liberated as an inorganic residue. Coal ash is composed of fly ash, dry-bottom boiler ash, wet-bottom boiler slag, cyclone boiler slag, and cinders. About 65 percent of the coal ash produced in the United States is fly ash (10). Fly ash is collected from the plant gases as a fine particulate residue. The size range of fly ash particles depends primarily on the type of collection system used. In general, fly ash particles will range in diameter from 1 to 150 microns (11).

In recognition of the many possible variations in chemical and physical properties, ASTM published C 350, a standard specification on fly ash for use as an admixture in concrete in 1954. In 1968, ASTM published C 618 which replaced C 350 and C 402, thereby bringing the provisions for both fly ash and natural pozzolan under a common specification. Until recent years, ASTM specifications as well as most published research were concerned with fly ash produced by bituminous coal. However, increased use of lignite coal and western coal plus the use of limestone and dolonite injection processes to achieve improved pollution control resulted in large quantities of fly ash which did not satisfy existing specifications. This ash had much higher calcium oxide contents and lower silicon oxide contents than ash usually obtained from bituminous coal. In 1977, ASTM revised C 618 by providing for two classes of fly ash; the more traditional fly ash was designated Class F while the fly ash with the higher calcium oxide content was identified as Class C.

3.3 Fly Ash in Portland Cement Concrete

3.3.1 Introduction

Fly ash or, more specifically, Class F fly ash has been used for many years. As a result, the advantages when Class F fly ash is used with portland cement have been well documented with the technology relatively well understood. Advantages resulting from the use of fly ash with portland cement include improved concrete properties and in some instances a reduction in cost. Some of the improved concrete characteristics reported by Abdun-Nur (4) in an evaluation of fly ash are: a lower water requirement, an improved workability, a lowered heat of hydration, a somewhat retarded time of set, an increased modulus of elasticity at later ages, and a reduced permeability. In addition, concrete with fly ash was reported to possess adequate freeze-thaw resistance.

Recently, however, the increased use of lignite and subbituminous coals has substantially increased the available quantities of Class C fly ash. Posed with the same disposal problems as with Class F fly ash, engineers are exploring the use of high lime fly ash with portland cement as a partial solution to the disposal problem. The technology, however, for using a Class C fly ash with portland cement is still in a developmental stage.

CHAPTER IV

EXPERIMENTAL PROGRAM

4.1 Introduction

Research activities were divided into two efforts, identified as tasks I and II. Task I dealt with the freeze-thaw durability of concrete; task II considered the characteristics of concrete cast at three different temperatures. Experimental details common to tasks I and II are provided in this chapter while details unique to a specific task are presented in Chapters V and VI.

The mix proportions were based on a Class A concrete as designated by the Standard Specifications for Highway Construction issued by the Oklahoma State Highway Commission. Batches used for control did not contain fly ash; in other batches, between 20 and 50 percent of the portland cement was replaced with fly ash on a weight basis. The quantities of mix water and air entraining agent (AEA) were adjusted to keep the slump and air content within specified limits.

4.2 Materials

4.2.1 Portland Cement

A single shipment of Type I portland cement was obtained for project use during the summer of 1980. After receipt in the laboratory, the cement was broken into lots of approximately 20 sacks and double wrapped in plastic film. A desiccant was placed between the two moisture barriers to further resist prehydration of the cement. The results of a laboratory analysis of the cement are given in Table I.

4.2.2 Fly Ash

The fly ash used in this study came from a coal fired generating plant near Muskogee, Oklahoma. A single shipment of fly ash provided in bags was used for all phases of the project. The fly ash was protected from moisture in the same manner as portland cement as described above.

The fly ash conformed to the requirements of a Class C mineral admixture as defined by ASTM Specifications for Fly-Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete (C 618-80). A laboratory analysis of the fly ash is given in Table II.

4.2.3 Concrete Aggregates

Aggregate was obtained from the stockpiles of a Stillwater, Oklahoma, ready-mix concrete firm. The fine aggregate was Arkansas River sand quarried near Sand Springs, Oklahoma. The coarse aggregate was crushed limestone obtained from two sources. The coarse aggregate used with the first series of freeze-thaw specimens in task I and with all concrete cast at 70 F (21 C) during task II was from a quarry near Drumright, Oklahoma. All other coarse aggregate was from a quarry near Pawnee, Oklahoma.

Aggregate was supplied as needed in small shipments of approximately 4 tons (3500 kg). The gradation of these shipments was somewhat

TABLE I

PORTLAND CEMENT PROPERTIES

Oxide/Compound Analysis, %	Determined by: Cement Manufacturer	Determined by: Independent Laboratory
SiO_2	21.18	21.80
Al_2O_3	5.45	6.14
Fe_2O_3	2.75	3.86
CaO	64.41	62.63
MgO	2.11	2.07
SO_3	3.07	3.29
C_3S	51.54	33.14
C_2S	21.56	37.70
C_3A	9.79	9.74
C_4AF	8.37	11.75
Loss on Ignition, %	1.02	0.77
Available Alkalies, %		
Na_2O	0.30	0.09[a]
K_2O	0.70	0.02[a]
Na_2O	0.76	---
Insoluble Residue, %	0.16	---
Physical Tests		
Fineness: Sq cm/gm	3866.00	---
Autoclave Expansion, %	0.027	---
Compressive Strength, KSI		
1 day	1680	---
3 days	3330	---
7 days	4200	---
Setting Time (Hrs/Min)		
Initial	2:40	---
Final	4:50	---

[a]Water soluble alkalies only.

1 ksi = 6.89 MPa.

TABLE II

FLY ASH PROPERTIES

Oxides, %	
SiO_2	30.00
Al_2O_3	23.24
Fe_2O_3	8.01
CaO	29.75
MgO	5.01
SO_3	3.58
Available Alkalies (Water Soluble), %	
Na_2O	0.24
K_2O	0.05
Moisture Content, %	0.12
Loss on Ignition, %	0.68
Physical Tests	
Fineness:	
Amount retained when wet sieved on No. 325, %	16.70
Pozzolanic Activity Index:	
With portland cement at 28 days, % of control	100.00
With lime at 7 days, ksi	0.990
Soundness, %	0.18
Specific gravity	2.64

1 ksi = 6.89 MPa.

variable. Because of segregation in the stockpile, the gradation of the aggregate also differed from that obtained from representative samples acquired by personnel of the Stillwater office of the Oklahoma Department of Transportation (ODOT). Based on a study of several ODOT gradation reports, typical gradations were established for the fine and coarse aggregates.

After delivery, aggregate was air dried to approximately constant weight. Both fine and coarse aggregates were sieved into three sizes. The small quantities of fine aggregate passing the No. 100 (150 μm) sieve and coarse aggregate passing the No. 8 (2.36 mm) sieve were wasted.

Prior to batching, the fine aggregate was recombined such that 20.5, 38.0, and 41.5 percent of the aggregate would be retained on No. 16, 30, and 100 sieves (1.18 mm, 600 μm, and 50 μm), respectively. The resulting aggregate has a fineness modulus of 2.71 and met gradation requirements of ASTM Specification for Concrete Aggregate (C 33-80). The fine aggregate had a specific gravity of 2.64 and an absorption capacity of 0.69 percent.

Coarse aggregate was recombined and met gradation requirements for ASTM C 33 size number 57. Based on the selected gradation, 22, 43, and 35 percent of aggregate would be retained on 3/4 in., 1/2 in., and No. 8 (19.0, 12.5, and 2.36 mm) sieves. The aggregate from Drumright had a specific gravity of 2.76, an absorption capacity of 0.91 percent, and a dry rodded unit weight of 104 pcf (238 kg/m^3). The stone from Pawnee had a specific gravity of 2.64, an absorption capacity of 1.39 percent, and a dry rodded unit weight of 98 pcf (224 kg/m^3).

4.2.4 Air-Entraining Admixture

Neutralized vinsol resin conforming to ASTM Specification for Air-Entraining Admixtures for Concrete (C 260-77) was used in all concrete batches.

4.3 Batching and Mixing of Concrete

The mix proportions for a Class A concrete used by ODOT were adopted for this study. The amount of mix water and AEA to provide a slump between 1 and 3 in. (25 and 75 mm) and an air content between 5 and 7 percent was established with trial mixes.

Approximately 24 hours prior to casting, water equal to 5 percent of the weight of the sand was blended into sand; the aggregate was then stored in a sealed container until the time of casting. At the same time the coarse aggregate was submerged in water.

All trial batches were 1.0 ft^3 (0.028 m^3) in volume; batches used for actual tests were 3.0 ft^3 (0.085 m^3). A rotating drum mixer with a maximum capacity of 3.75 ft^3 (0.106 m^3) was used for all work. The mixer was initially charged with aggregate and a portion of the mix water containing all of the AEA. The mixer was started; one-half of the cement, more water, the remainder of the cement, and the last of the mix water were added. The mixer was operated for three minutes after the addition of water, shut off for three minutes, and then operated for two more minutes. For the test batches containing fly ash, the fly ash was batched with the cement and added to the mix in the manner previously described.

4.4 Study of the Hardened Air Void System

ASTM Recommended Practice for the Microscopical Determination of

Air-Void Content and Parameters of the Air-Void System in Hardened Concrete (C 457-71) indicates that a minimum surface area of 12 in.^{2} (77 mm^2) is needed to establish the total air content for a concrete containing aggregate with a nominal maximum size of 1 in. (25 mm). In addition, for tests using the Linear Traverse Method of ASTM C 457, a minimum traverse of 95 in. (2413 mm) is specified.

Samples approximately 1 by 3 by 4 in. were obtained from the prisms by sawing transverse to the axis of the specimens. One sample was obtained from each of the three prisms cast from each batch during task I work; the samples were taken from near mid-length. Two samples taken at approximately the third-points were obtained from each prism cast during task II efforts.

After polishing, specimens were studied using a microscopic apparatus which satisfied the requirements of ASTM C 457. The microscope stage was attached to a DCDT-style displacement transducer which was connected to a computer-based data acquisition system which permitted automatic distance measurements and storage of data.

Approximately 100 in. (2500 mm) of linear transverse was distributed over the three samples from task I prisms and the two samples from task II prisms. At the time the microscope work commenced, it was not felt that technicians could reliably distinguish between the paste and aggregate phases. Therefore, a calculated paste content based on the mix proportions and specific gravities of the materials was used in the calculation of the spacing factor.

CHAPTER V

FREEZE-THAW DURABILITY

5.1 Background

The resistance of concrete to freeze-thaw action is increased by air entrainment--the incorporation of small air bubbles in the paste matrix during mixing. The benefits of air entrainment were accidentally discovered after beef tallow was used as a grinding aid in the manufacture of portland cement. It has been shown (12, 13) that small air bubbles help relieve hydraulic pressure developed as free water--especially in capillary voids--is converted to ice during freezing. The effectiveness of air entrainment is closely tied to the proximity of an air bubble to a location where ice is being formed (14). As a result, the quality of the internal air void system is usually described quantitatively in terms of the spacing factor, which is the maximum distance of any point in the cement paste from the periphery of an air void; or the specific surface, which is the surface area of the air voids per unit volume; or both. An entrained air system which has a small spacing factor and a large specific surface is desired. Hence entrained air in the form of microscopic air bubbles is an ideal situation. A spacing factor of 0.008 in. (0.2 mm) is usually considered to provide a durable concrete (14, 15).

The spacing factor and specific surface can only be measured by a microscopic examination of the hardened air void system; for field and laboratory control of entrained air, reliance must be placed on a measurement of the total air content. Such measurements by pressure or volumetric techniques include large accidentally entrapped air bubbles not removed by consolidation as well as the entrained air and are expressed as a percentage of total volume rather than volume of paste.

Entrained air voids are generally considered to range in diameter from 10 to 1000 μm; while entrapped air voids are larger and usually less spherical, any size distinction is arbitrary. However, larger bubbles are more easily eliminated by vibration and other placing and finishing operations. Thus, circumstances which result in an entrained air system tending toward smaller air voids is also a system which is more stable and more likely to be present in situ.

The use of fly ash can significantly alter the AEA demand of a mix. Most researchers agree that the AEA demand is strongly related to the carbon content of the fly ash (16-24). Apparently, the high surface area associated with carbon absorbs part of the AEA, thereby reducing the amount available to entrain air (25). Meininger (26) reported that if fly ash has a low AEA demand, then air content increase is proportional with AEA. However, if the fly ash has a high AEA demand, then the curve is no longer proportional and may be "S" shaped. The irregular curve suggests that the AEA requirement will not be predictable when high carbon ashes are used. Meininger suggests using a foam index test as a good quality control measure. The foam index is the minimum amount of AEA necessary to produce a stable foam. Halstead (10), in a report for the Virginia Department of Highways and Transportation, indicates that erratic amounts of entrained air are minimized when the loss on ignition (which is a means to measure carbon content) is 3 percent or less.

Carbon content is only one characteristic of fly ash which can influence AEA demand. For example, Snyder et al. (28) found that the total surface area of the fly ash, measured by a gas adsorption method, was a better indicator of AEA demand than carbon content. Other reports indicate similar results, in that the fineness associated with fly ash can compound the influence of carbon content (27, 29).

As discussed in section 6.1.2 of this study, fly ash can influence the quantity of mix water. It has been shown (30) that as the water-to-cement ratio is increased, the spacing factor increases for mixes containing equal quantities of air. As a result, when the characteristics of a fly ash used in concrete permit a reduction in mix water, a trend to smaller, more closely spaced air voids may result.

Soluble alkalies, usually expressed as Na_2O, can also affect the AEA demand of a mix. In tests where Na_2O was added to the mix water--a procedure which was assumed to have no influence on the normal rate of release of alkalies from the cement--Greening (31) found that the water soluble alkalies reduced the amounts of AEA (a neutralized vinsol resin) required to produce constant air contents. It was suggested that the amount of soluble alkalies which will optimize the vinsol resin requirements of a cement mortar is 0.8 percent of the weight of the mix water. Although water soluble alkalies may reduce AEA demand, Pistilli (32) indicated that the alkalies can also increase the spacing factor, which is the average distance between air voids of the hardened paste. Increasing the spacing factor of the hardened concrete decreases the effectiveness of the air void system. Pistilli found when the water soluble alkali as a percent of the mix water was increased from less than 1.0 percent to 2.0 percent, the neutralized vinsol resin AEA produced void systems with progressively higher spacing factors. Because Class C fly ashes sometimes have relatively high alkali contents, this topic will probably receive additional research.

Freeze-thaw data regarding concrete made with lignite or subbituminous fly ash is limited. In a report by Dobie and Henning (33), cement was replaced with lignite fly ash in percentages up to 35 percent. The samples were tested in accordance with ASTM C 666, procedure A, with deterioration measured as a reduction in relative dynamic modulus, which is a measure of internal rigidity. Concrete was resistant to damage; the largest reduction in the relative dynamic modulus was only 11 percent at an ash replacement of 35 percent.

Dunstan (34) subjected specimens containing lignite and subbituminous fly ash from five different sources to freeze-thaw cycles in water. Each cycle consisted of 1.5 hours at 10 F (-12.2 C) followed by 1.5 hours at 70 F (21 C). Weight loss was used as a means to measure deterioration. The five fly ashes did not meet ASTM requirements for either Class F or Class C fly ash. However, four of the ashes met most of the oxide requirements for a Class C fly ash, while the fifth ash met the oxide requirements for a Class F fly ash. Specimens which withstood 800 freeze-thaw cycles with a weight loss of more than 25 percent were given an excellent durability rating; only the concrete made with the subbituminous fly ash resembling a Class F failed to achieve an excellent rating.

5.2 Experimental Procedures

Immediately following the mixing operation, the concrete was discharged from the mixer, and the temperature, slump, air content, and unit weight were measured. Six 6 by 12-in. (152 by 305-mm) cylinders and six 3 by 4 by 16-in. (76 by 102 by 406-mm) prisms were cast from each batch. Specimens were removed from molds after 24 hours; cylinders were placed in a fog room with a relative humidity greater than 95 percent, and prisms were placed in lime-saturated water; specimens were maintained at a temperature of 73.4 ± 3 F (23 ± 1.7 C).

Fourteen days after casting, two of the cylinders from each batch were tested in compression, and three prisms from each batch were weighed and placed in a water bath maintained at 42 F (5.6 C). After approximately two hours, the prisms were tested for transverse frequency in accordance with ASTM Test for Fundamental Transverse, Longitudinal and Torsional Frequencies of Concrete Specimens (C 215-60) using equipment shown in Figure 1. Prisms were then subjected to durability testing in accordance with Procedure A, ASTM Test for Resistance of Concrete to Rapid Freezing and Thawing (C 666-77) using the apparatus shown in Figure 2. The fundamental transverse frequency and weight of prisms were determined after intervals of approximately 30 cycles of exposure to the freezing-thawing cycles. Three hundred freeze-thaw cycles were applied. Twenty-eight days after casting, two additional cylinders were tested in compression. Two cylinders and three prisms from each batch were not tested.

5.3 Experimental Results

Tables III, IV, and V contain data pertaining to the three series of freeze-thaw durability tests. During the preparation of batches containing various amounts of fly ash, it was found that as the percentage of ash was increased it was generally necessary to increase the amount

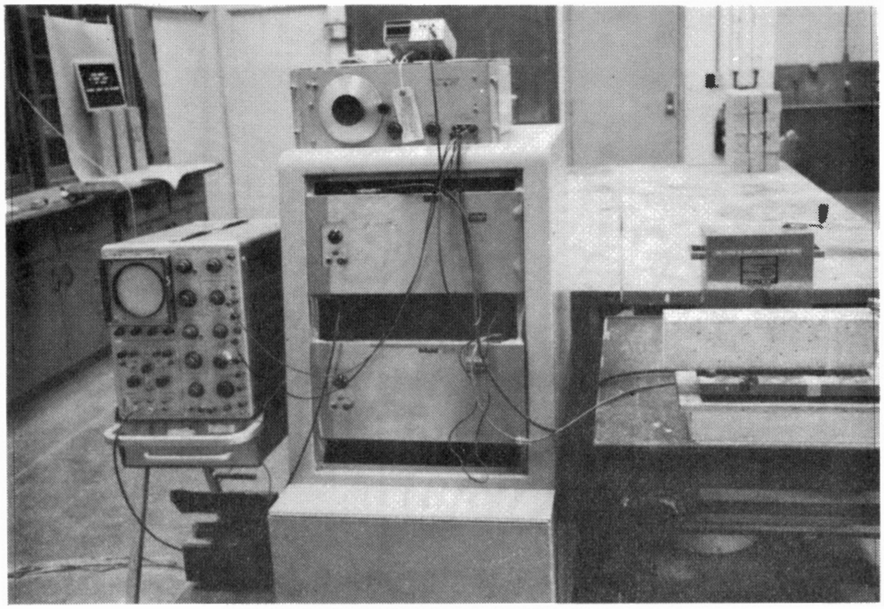

Figure 1. Equipment Used to Determine the Fundamental Transverse Frequency

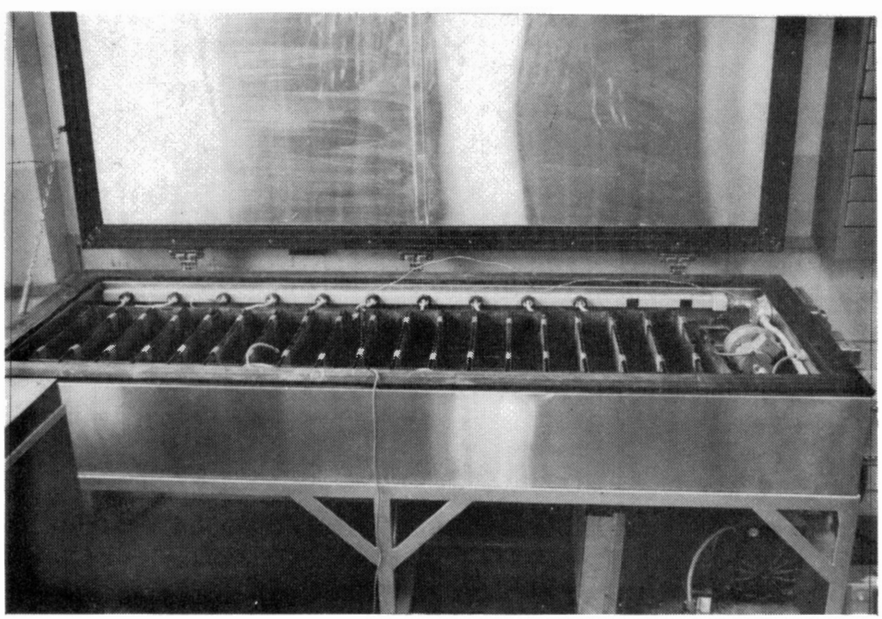

Figure 2. 18 Prism Capacity Freeze-Thaw Cabinet

TABLE III

CONCRETE DATA FOR TASK NO. 1, SERIES NO. 1

Item	Percent Fly Ash 0	20	30	40	50
Quantities Per Yd^3					
Cement (lb)	564	452	395	338	282
Fly Ash (lb)	0	112	169	226	282
Water (lb)	254	198	194	192	199
Fine Agg. (lb)	1170	1170	1170	1170	1170
Coarse Agg. (lb)	2064	2064	2064	2064	2064
Air Ent. Agent (ml)	225	270	297	324	351
Properties of Fresh Concrete					
Slump (in.)	$2\frac{1}{4}$	$1\frac{1}{2}$	$1\frac{1}{2}$	1	$3\frac{1}{4}$
Air Content (%)	5.8	5.3	5.7	5.5	6.6
Unit Weight (lb/ft^3)	151	148	147	149	147
Water/Cement Ratio	0.45	0.35	0.35	0.34	0.35
Concrete Temperature, C	21	20	21	21	22
Compressive Strength					
14 days (ksi)	4.73	4.90	4.66	4.14	3.00
28 days (ksi)	5.56	5.97	5.76	5.18	4.06
Static Modulus of Elasticity					
14 days (ksi)	4410	4450	4180	4590	3640
28 days (ksi)	4350	4640	4450	5020	4180
Freeze-Thaw Durability Factor					
Specimen 1	100.6	97.8	87.2	94.3	97.6
Specimen 2	97.6	92.2	91.5	92.0	98.2
Specimen 3	95.6	89.9	94.4	103.0	102.3
Average	97.9	93.3	91.0	96.4	99.4
Average Weight Loss (grams)	156	171	263	243	262
Hardened Air Content (%)	3.1	6.5	7.9	9.4	3.4
Specific Surface ($in.^2/in.^2$)	357	371	256	229	456
Spacing Factor (in.)	0.016	0.010	0.012	0.011	0.012

1 lb/yd^3 = 0.593 kg/m^3; 1 ml/yd^3 = 1.31 ml/m^3; 1 in. = 25.4 mm; 1 ksi = 6.89 MPa; 1 lb/ft^3 = 16.0 kg/m^3; 1 $in.^2/in.^3$ = 0.0394 mm^2/mm^3.

TABLE IV

CONCRETE DATA FOR TASK NO. 1, SERIES NO. 2

Item	Percent Fly Ash				
	0	20	30	40	50
Quantities Per Yd^3					
Cement (lb)	564	452	395	338	282
Fly Ash (lb)	0	112	169	226	282
Water (lb)[a]	---	---	---	---	---
Fine Agg. (lb)	1170	1170	1170	1170	1170
Coarse Agg. (lb)	2064	2064	2064	2064	2064
Air Ent. Agent (ml)[a]	---	---	---	---	---
Properties of Fresh Concrete					
Slump (in.)[a]	---	---	---	---	---
Air Content (%)[a]	---	---	---	---	---
Unit Weight (lb/ft^3)[a]	---	---	---	---	---
Water/Cement Ratio[a]	---	---	---	---	---
Concrete Temperature, C[a]	---	---	---	---	---
Compressive Strength					
14 days (ksi)	4.96	3.26	4.77	4.22	3.51
28 days (ksi)	5.24	3.67	5.59	4.53	3.84
Static Modulus of Elasticity					
14 days (ksi)	4400	3840	4410	4030	3710
28 days (ksi)	4480	3830	4360	4120	4070
Freeze-Thaw Durability Factor					
Specimen 1	85.9	95.5	87.0	93.1	93.2
Specimen 2	73.7	93.3	78.4	89.0	97.6
Specimen 3	97.8	98.1	88.0	83.3	91.3
Average	85.8	95.6	84.5	88.5	94.0
Average Weight Loss (grams)	158	364	130	176	232
Hardened Air Content (%)	1.7	12.2	9.0	10.4	4.5
Specific Surface ($in.^2/in.^2$)	323	207	284	323	300
Spacing Factor (in.)	0.023	0.009	0.009	0.007	0.016

[a]Data not available.

1 lb/yd^3 = 0.593 kg/m^3; 1 ml/yd^3 = 1.31 ml/m^3; 1 in. = 25.4 mm; 1 ksi = 6.89 MPa; 1 lb/ft^3 = 16.0 kg/m^3; 1 $in.^2/in.^3$ = 0.0394 mm^2/mm^3.

TABLE V

CONCRETE DATA FOR TASK NO. 1, SERIES NO. 3

Item	Percent Fly Ash				
	0	20	30	40	50
<u>Quantities Per Yd^3</u>					
Cement (lb)	564	452	395	338	282
Fly Ash (lb)	0	112	169	226	282
Water (lb)	225	190	179	182	177
Fine Agg. (lb)	1170	1170	1170	1170	1170
Coarse Agg. (lb)	2064	2064	2064	2064	2064
Air Ent. Agent (ml)	216	270	297	324	351
<u>Properties of Fresh Concrete</u>					
Slump (in.)	1	$1\frac{3}{4}$	$1\frac{1}{2}$	2	2
Air Content (%)	5.0	5.7	5.0	5.5	5.7
Unit Weight (lb/ft^3)	147	146	147	146	145
Water/Cement Ratio	0.40	0.34	0.32	0.32	0.31
Concrete Temperature, C	24	23	23	23	22
<u>Compressive Strength</u>					
14 days (ksi)	5.93	5.26	5.56	5.24	4.63
28 days (ksi)	6.33	6.04	5.92	5.98	5.21
<u>Static Modulus of Elasticity</u>					
14 days (ksi)	4160	4100	4140	3960	3690
28 days (ksi)	4240	4170	4270	4260	3930
<u>Freeze-Thaw Durability Factor</u>					
Specimen 1	92.3	90.6	99.6	96.2	94.8
Specimen 2	93.1	92.8	90.3	105.2	99.8
Specimen 3	95.6	95.3	68.0	81.2	100.2
Average	93.7	92.9	86.0	94.2	98.3
Average Weight Loss (grams)	31	63	18	13	44
Hardened Air Content (%)	3.1	3.9	2.3	11.4	3.0
Specific Surface (in.^{2}/in.^{2})	283	267	318	217	341
Spacing Factor (in.)	0.020	0.019	0.020	0.010	0.017

1 lb/yd^3 = 0.593 kg/m^3; 1 ml/yd^3 = 1.31 ml/m^3; 1 in. = 25.4 mm; 1 ksi = 6.89 MPa; 1 lb/ft^3 = 16.0 kg/m^3; 1 in.^{2}/in.^{3} = 0.0394 mm^2/mm^3.

of AEA and to reduce the amount of mix water. The percentage of fly ash did not strongly influence the compressive strength or the modulus of elasticity.

In no case was it necessary to terminate testing until the 300 cycles of exposure prescribed by ASTM C 666 had been applied. As a result, the durability factors which are reported in the tables are the square of the ratio of the fundamental frequency after 300 cycles of freezing to the initial fundamental frequency. In a few cases the durability factor is greater than 100. This suggests that either slight additional hydration took place during the durability testing or that the initial fundamental frequency was slightly in error.

Durability factors based on the average of three specimens from each batch ranged from approximately 85 to almost 100.

Photographs of the prisms after 300 cycles of freezing are provided in Figures 3 through 7. From a visual standpoint only superficial damage was experienced by the specimens.

After completion of durability tests on the second series of specimens, it was discovered that original data regarding mix water, AEA, air content, slump, unit weight, and temperature of the concrete were missing from the laboratory. While potentially useful data are unavailable, it is known that for all five batches the slump and air content were within limits.

5.4 Discussion of Results

Durability factors from the three series of specimens containing the various fly ash percentages were averaged, giving the following results: 20 and 40 percent fly ash specimens had approximately constant durability

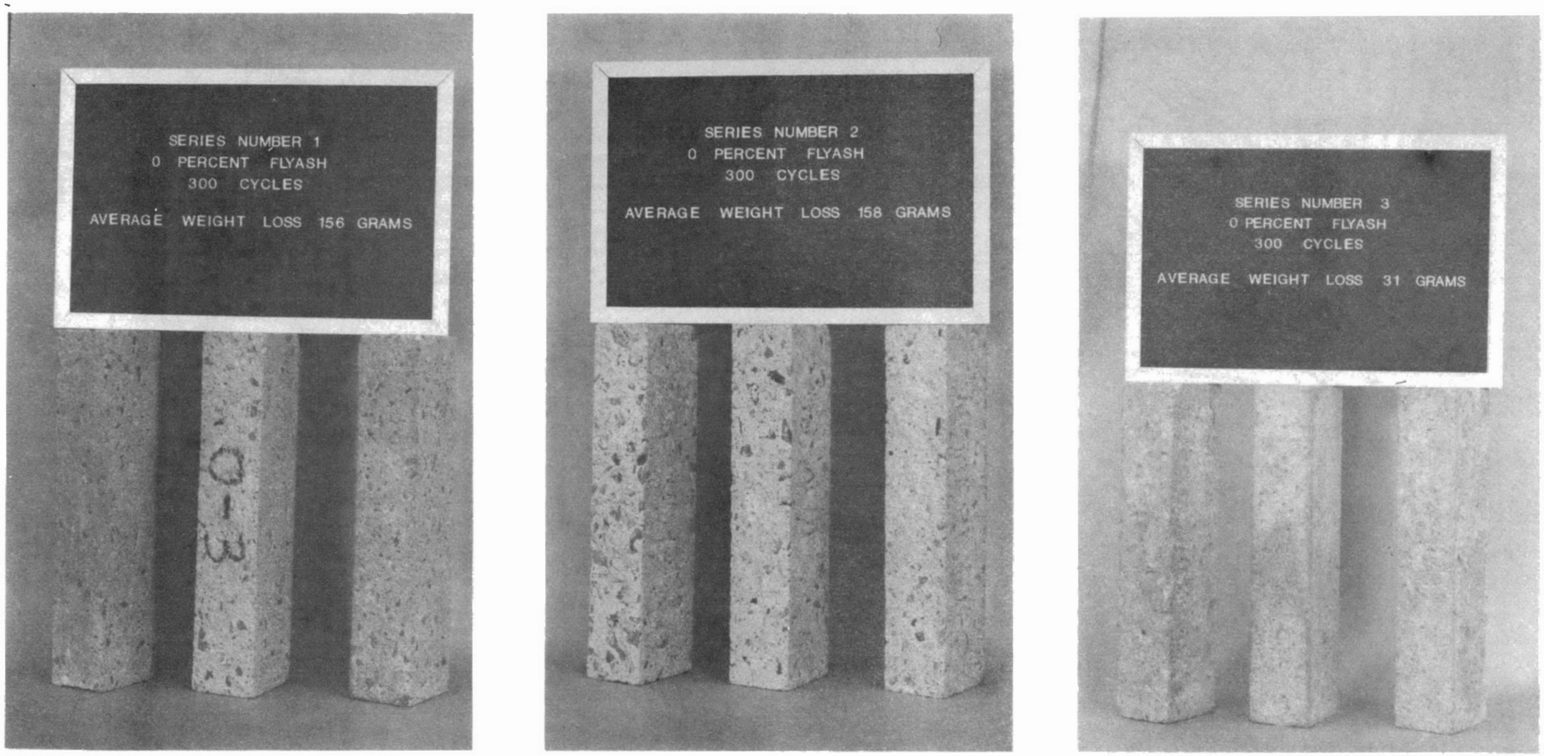

Figure 3. Specimens With 0% Fly Ash After Freeze-Thaw Tests

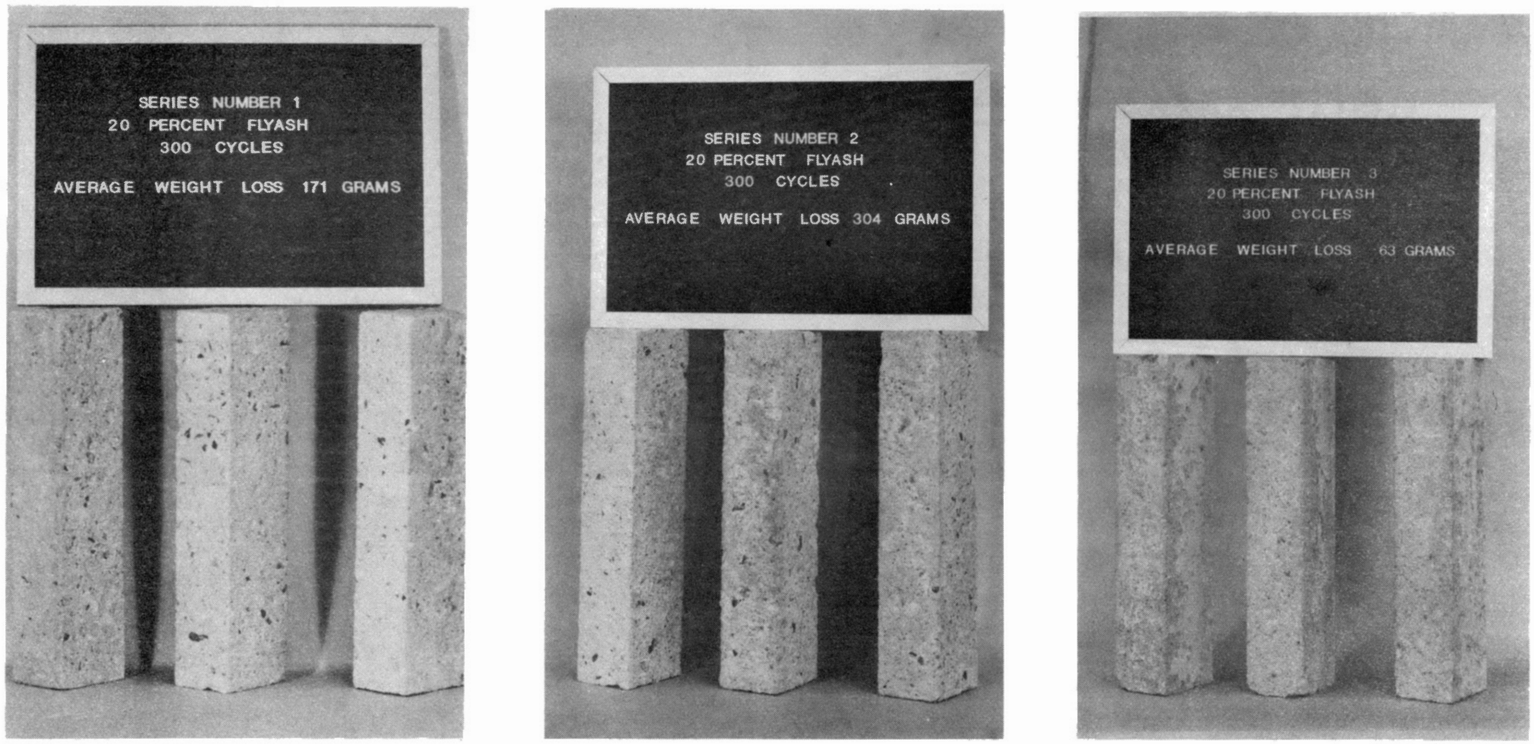

Figure 4. Specimens With 20% Fly Ash After Freeze-Thaw Tests

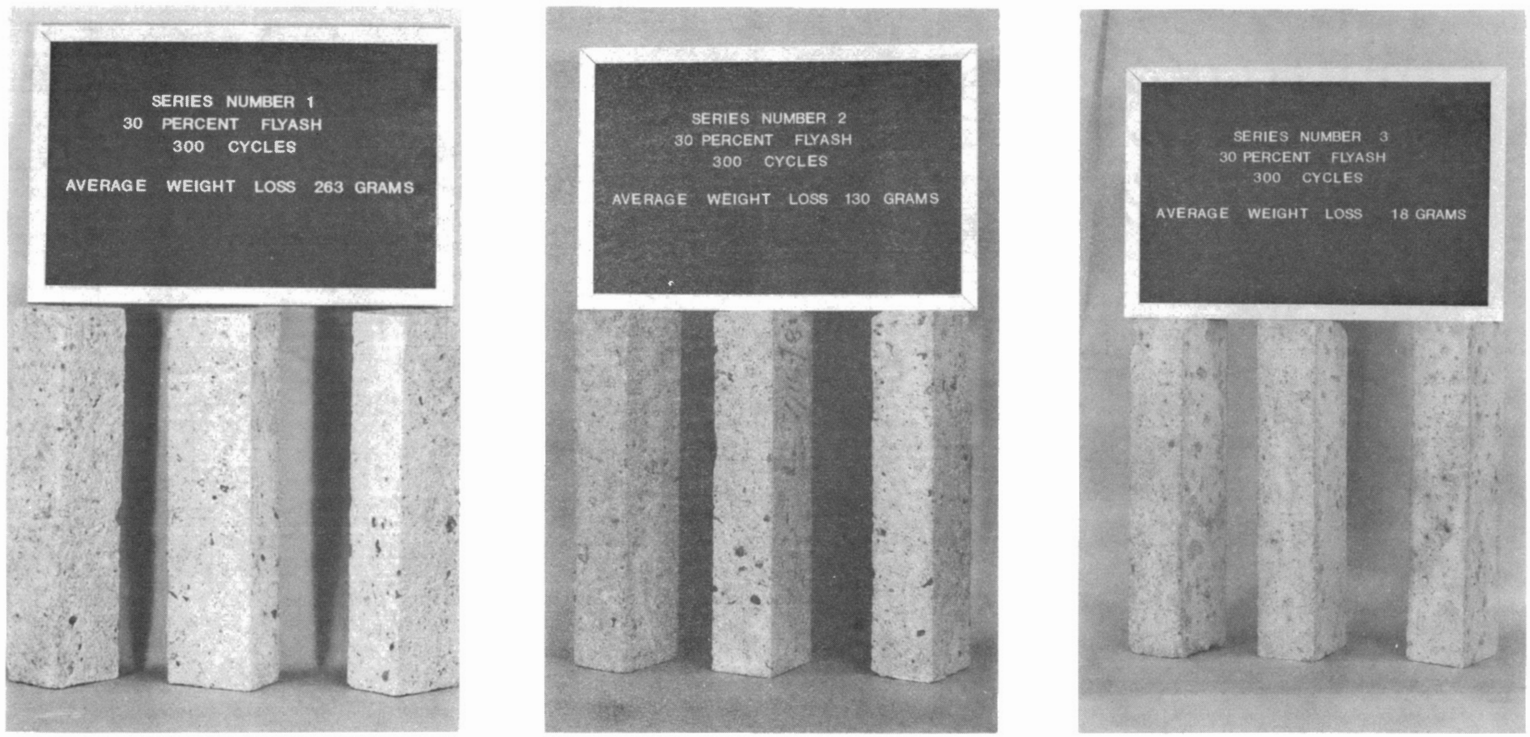

Figure 5. Specimens With 30% Fly Ash After Freeze-Thaw Tests

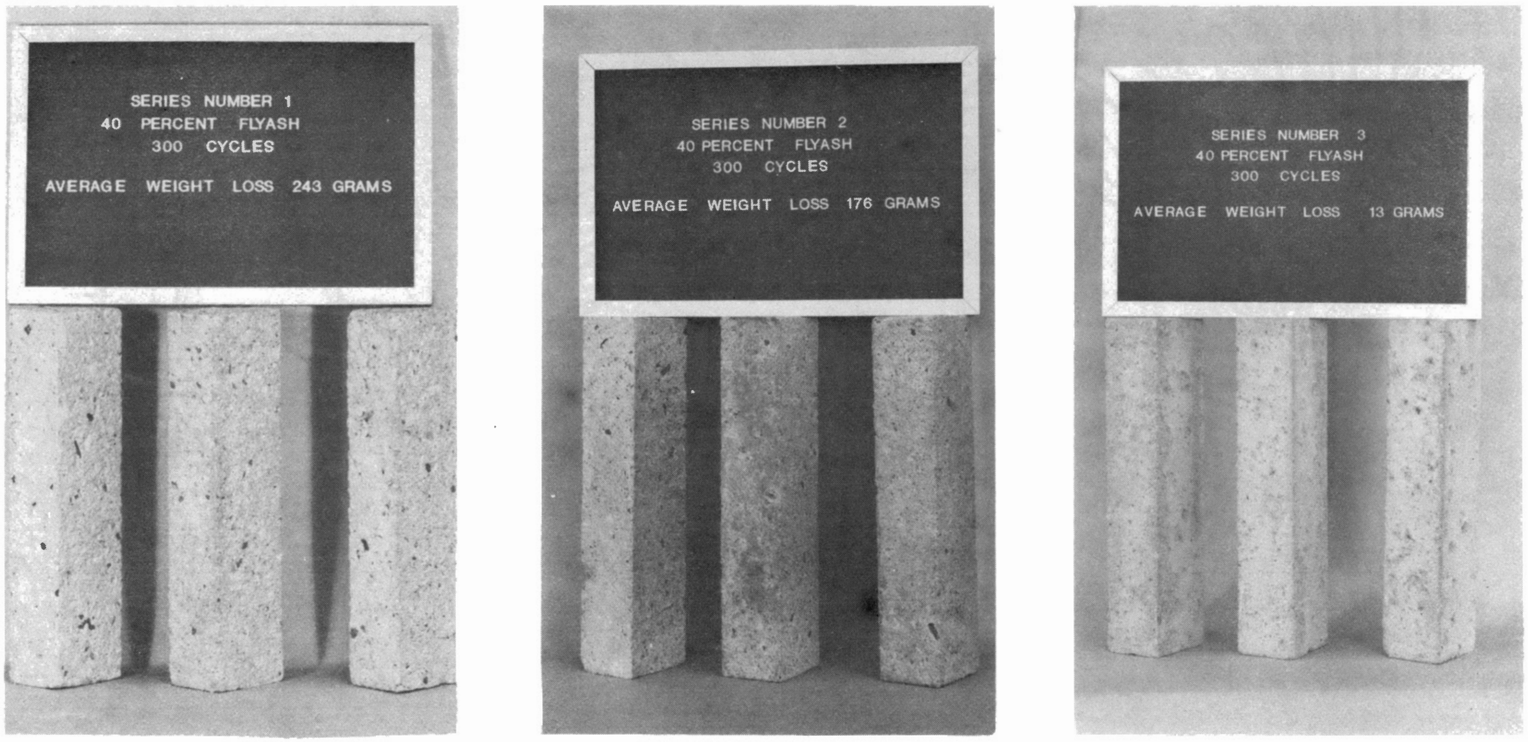

Figure 6. Specimens With 40% Fly Ash After Freeze-Thaw Tests

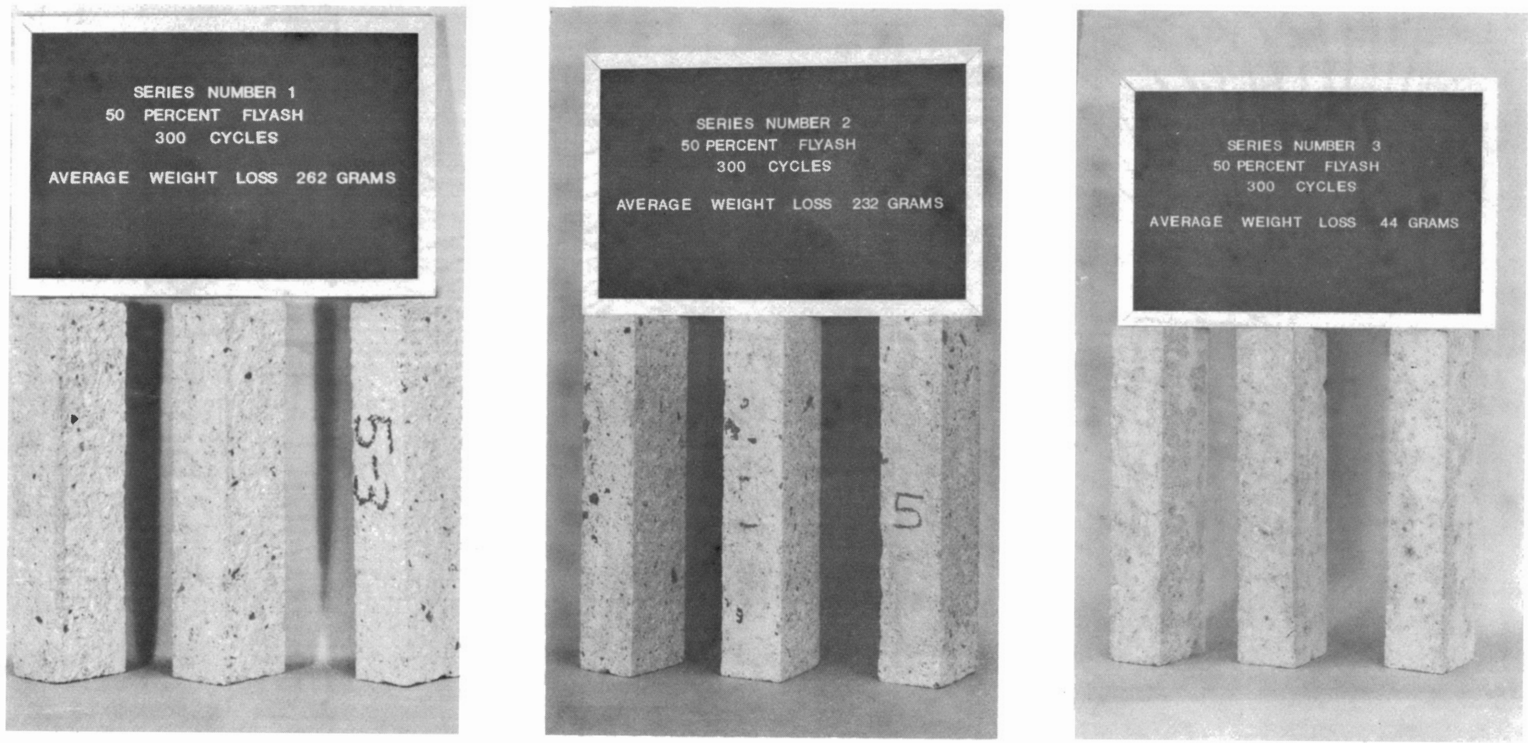

Figure 7. Specimens With 50% Fly Ash After Freeze-Thaw Tests

factors with values of 94 and 93 percent, respectively; control specimens were slightly lower by about 1.5 percent; specimens for the remaining two fly ash percentages of 30 and 50 percent were determined to be 88 and 97 percent, respectively. The relatively high durability factors from three series of specimens indicate that internal deterioration caused by rapid freezing and thawing is not significantly influenced by cement replacement with fly ash. Information provided in Tables III, IV, and V indicates that most samples had an acceptable air void system. In some instances the surfaces appeared to have either greater or smaller percentages of mortar than was typical. Since the air void parameters were based on a computed paste content, this factor influences the accuracy of these data to an unknown degree. In Figure 8 the durability factor is plotted against the percent fly ash; no trend is apparent between durability and percent fly ash replacement.

Weight loss data do not correlate well with durability factors. For example, relatively high durability factors were obtained from specimens containing 20 and 50 percent fly ash; however, the prisms from these two mixes had the largest individual average weight losses. As can be seen in Figure 9, there appears to be a strong correlation between weight loss and compressive strength at the initiation of freeze-thaw testing; no relationship between percent fly ash and weight loss is apparent. It is doubtful that weight loss is dependent on compressive strength per se; lower strength concrete are usually more porous and thus more susceptible to frost damage.

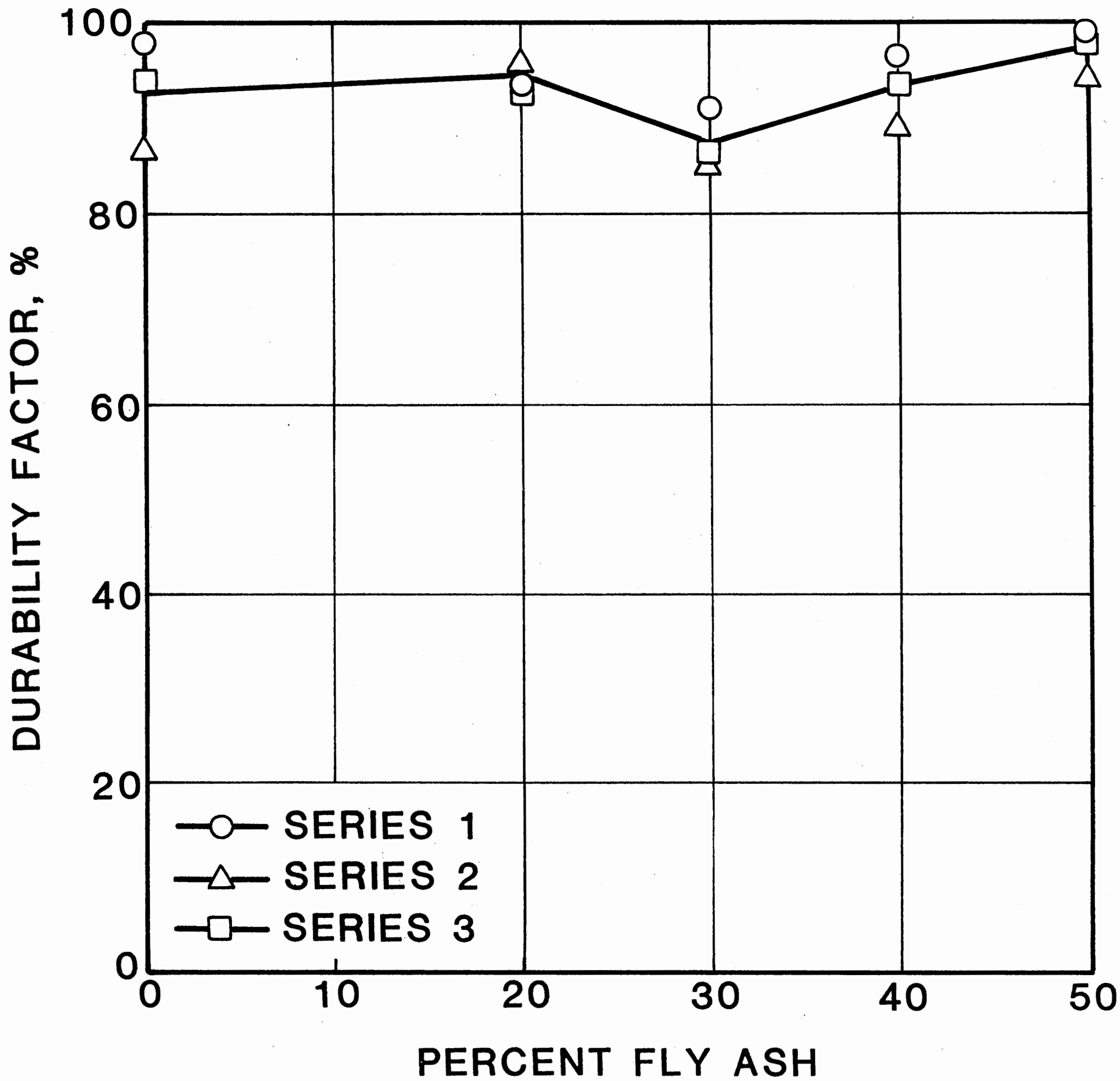

Figure 8. Influence of Percent Fly Ash on Freeze-Thaw Durability

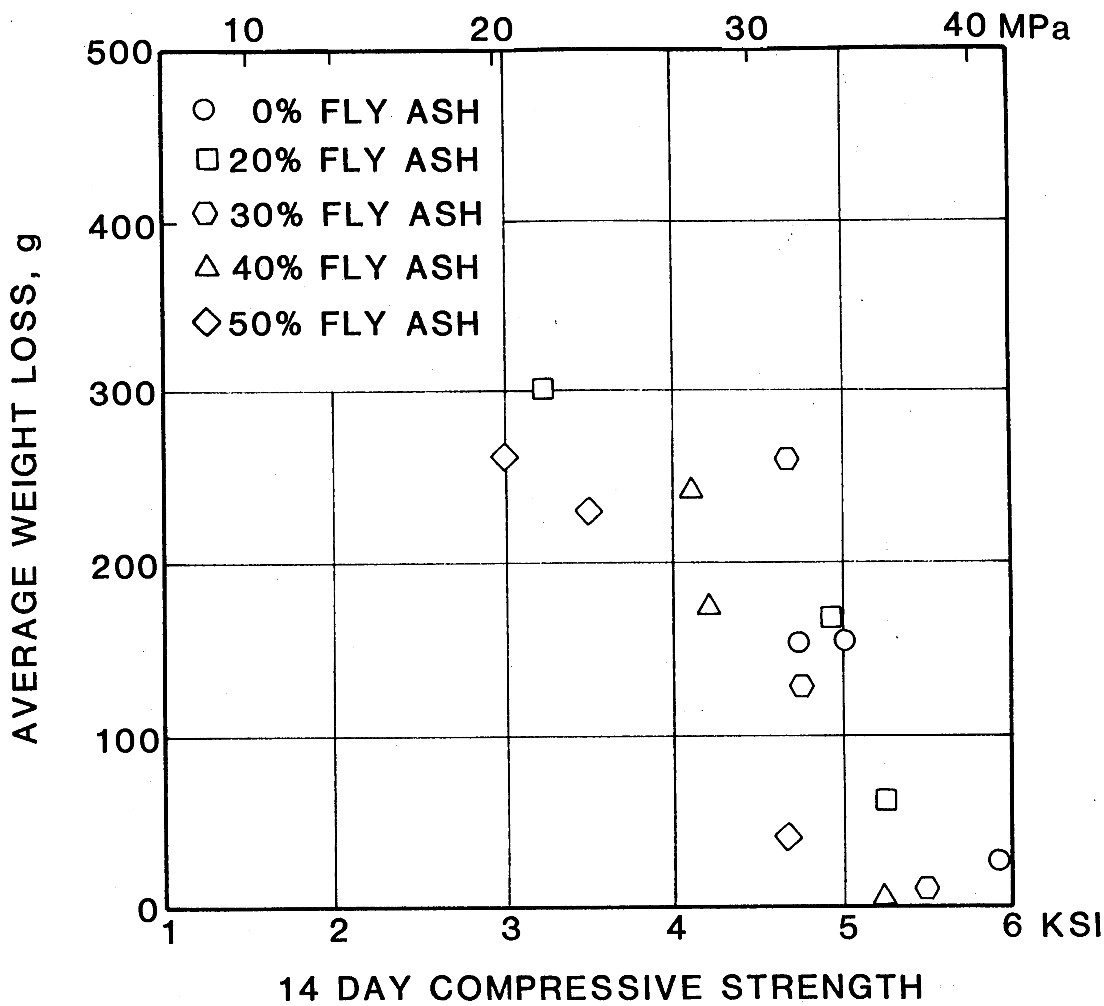

Figure 9. Influence of Compressive Strength on Weight Loss

CHAPTER VI

INFLUENCE OF FLY ASH ON CHARACTERISTICS OF CONCRETE

6.1 Background

6.1.1 Introduction

It is becoming increasingly apparent that fly ash cannot be regarded as a generic admixture for concrete. The physical and chemical properties of fly ash can vary greatly, depending on the source of coal, the type of equipment used for combustion, and collection and operating conditions at the time of combustion. As a result, the literature contains numerous conflicting observations. In the following sections, the influence of fly ash on selected topics within the general scope of this research program will be presented. To the extent possible, information is provided which is probably correct for the type of fly ash used in this study; an effort has been made to exclude information on ashes not similar to those presently available in Oklahoma. Thus most information is based on tests involving fly ash with high fineness, low carbon, and --to the extent possible--high lime.

6.1.2 Influence of Fly Ash on Mix Proportions

Fly ash particles are small in size and somewhat spherical in shape, resulting in a ball-bearing effect which allows the concrete particles to flow with less friction. Numerous studies are cited by Abdun-Nur (4), Berry and Malhotra (11), and Snyder et al. (28) where concretes with fly ash exhibit improved workability and require less water compared to portland cement concrete with the same consistency. However, these authors also cite a few studies where the fly ash has resulted in an increase in the water requirements of the mix--usually as a result of relatively high carbon content. In an evaluation of fly ash concrete, Abdun-Nur (4) reported that reduced bleeding and reduced segregation were observed repeatedly by many investigators. In some instances, the improved workability associated with the presence of fly ash may permit some modification in the ratio of fly ash plus cement to total aggregate or ratio of fine aggregate to coarse aggregate.

In addition, fly ash can improve the finishing characteristics of concrete. In certain cases, concrete finishers who worked with fly ash in the past specifically requested fly ash concrete (35).

The influence of fly ash on AEA demand is apparently variable as previously discussed in section 5.1.

6.1.3 Retarding Action of Fly Ash

Davis et al. (36) reported that in all cases the time of set for fly ash-portland cement concretes was greater than for concretes containing no fly ash. Snyder et al. (28), however, reported conflicting results. In their report three methods were used to measure setting times of mortar. One method was based on evolution of heat associated with hydration, while the second and third methods used the ASTM Vicat test. In some tests the water-to-cement (w/c) ratio was constant and in other tests the w/c ratio was varied in order to maintain a constant consistency. Results from the first method indicated that the temperature peak associated with initial and final set was not influenced by the use of fly ash. In the second method, when the w/c ratio was held constant, the time of set appeared to increase with the addition of fly ash. However, the increase appeared to be a function of consistency rather than fly ash, as the less fluid mixes tended to set first. Results from the third test concluded that the addition of fly ash did not significantly increase the time of set of the mix.

6.1.4 Strength and Curing Conditions

A valuable property of fly ash is its pozzolanic nature. As previously discussed, fly ash will react with the free lime produced by the hydration of portland cement in the presence of moisture to produce a stable cementing medium. This quality produces a substantial increase in strength at later ages. While this increase in strength is beneficial, most researchers have found that when a Class F fly ash is used to replace a portion of the portland cement, lower earlier strengths result. In order to attain equivalent or higher strengths than a plain concrete at an early age, studies have shown that Class F fly ash can be added in greater quantities than the portland cement removed or used to replace a portion of the fine aggregate. Abdun-Nur (4), Berry and Malhotra (11), and Snyder et al. (28) cite numerous studies involving such results. In order to obtain improved strength at later ages with Class F fly ash, prolonged curing may be necessary (37).

Although a number of studies have been conducted and others are underway involving Class C fly ash, few results have yet been published. Recently, Cook (39) has presented results which show that when 20 to 30 percent of the portland cement is replaced with Class C fly ash on a weight basis, there is a significant increase in compressive strength at all ages. However, possibly because of the retarding action of the fly ash, the 1- and 3-day compressive strengths cannot be used to predict the strength at 28 days. Cook points out that the use of Class C fly ash permitted a lower w/c ratio which was beneficial to strength.

In earlier work with lignite and subbituminous fly ash, Dunstan (34) held the w/c ratio and slump constant, which resulted in a lower total weight of cementitious materials per unit volume. Although lower in strength than the control mix, concretes made with lignite and subbituminous fly ash exhibited better strengths than concrete with a Class F fly ash--especially at early ages.

In general construction, Class F fly ash has seen limited usage because of the need of prolonged curing if the full potential of the cement and fly ash are to be realized. Findings such as those of Davis et al. (36), where fly ash concrete is weaker at early ages but considerably stronger than conventional concrete at later ages, have found their way into most references on concrete materials. The limited data discussed above suggest that concrete made with Class C fly ash may be more suitable for general purpose applications.

Washa and Withey (19) and Bloem (20) report that adverse curing conditions influence the pozzolanic reaction in the same manner as the hydration of portland cement. However, Bloem (20) reported that while low temperature or lack of moisture produces a similar detrimental influence on fly ash and plain concrete, fly ash concrete lost the benefit of higher strength at later ages. The influence of adverse curing conditions on the properties of concrete made with Class C fly ash have not been reported.

6.1.5 Modulus of Elasticity

Davis et al. (36) reported the initial tangent modulus of elasticity was apparently a function of strength. Three fly ash-portland cement concrete mixes were compared with a mix containing no fly ash, with the modulus of elasticity measured in intervals of 7, 28, 90, and 365 days. On the average, the modulus of elasticity for the fly ash-portland cement mixes were lower at 7 and 28 days. The corresponding compressive strengths were also somewhat lower. The modulus of elasticity and compressive strengths for 90 and 365 days, however, were higher in all cases. The report concludes that the variation in elasticity from lower at earlier ages to higher at later ages than concretes containing no fly ash is not significant enough to affect design.

6.2 Experimental

Mixing and testing of plastic concrete, including time of set, was performed in a test chamber maintained at 55, 70, or 90 F (13, 21, or 32 C). Prior to mixing, all materials and equipment were placed in the chamber and allowed to reach temperature equilibrium.

After initial mixing, concrete was discharged from the mixer. The temperature, slump, air content, and unit weight were measured in accordance with relevant ASTM procedures. Three 6 by 12-in. (152 by 305-mm) cylinders, one 3 by 4 by 12-in. (76 by 102 by 406-mm) prism, and one 6-in. (152-mm) cube were cast. All specimens were cast in steel molds which had been sealed with wax. The cube which was cast with mortar screened from the concrete using a No. 4 (9.75 mm) sieve was tested in accordance with ASTM Test for Time of Setting of Concrete Mixtures by Penetration Resistance (C 403-77).

Unused concrete including that used in the slump and air content tests was returned to the mixer which was restarted at a reduced speed of 2 rpm. At 30-minute intervals or until the concrete became unworkable, the mixer was stopped and the temperature, slump, air content, and unit weight were measured and a single prism was cast.

Cylinders and prisms were removed from the casting chamber after 24 hours. Specimens cast with fly ash at 55 F (13 C) were sometimes too weak to be removed from molds at this time; in such cases, specimens were exposed to ambient laboratory temperature for several hours. The cylinders were cured in a moist room described above, and tested in compression after 28 days. The prisms which were used to obtain samples for microscopic examination of the hardened air void system were cured in the moist room for a minimum of 28 days.

6.3 Experimental Results

6.3.1 Mix Proportions

Tables VI, VII, and VIII present mix proportions for concrete cast at 55, 70, and 90 F (13, 21, and 32 C). The w/c ratio is the ratio of the weight of water to the weight of cement plus fly ash--the latter weight constant. In Figure 10, it can be seen that the mix water tends to decrease as the percent fly ash increases. No definite trend is apaparent regarding mix temperature and water demand. As can be seen in Figure 11, AEA demand increased as percent fly ash increased and as the temperature of the mix increased.

6.3.2 Properties of Concrete

As shown in Figure 12, as the percent fly ash was increased the

TABLE VI

CONCRETE DATA FOR TASK NO. 2, 55 F (13 C)

Item	Percent Fly Ash									
	0		20		30		40		50	
Batch	1	2	1	2	1	2	1	2	1	2
Quantities Per Yd^3										
Cement (lb)	564	564	452	452	395	395	338	338	282	282
Fly Ash (lb)	0	0	112	112	169	169	226	226	282	282
Water (lb)	230	236	221	216	209	209	188	189	182	195
Fine Agg. (lb)	1192	1192	1192	1192	1192	1192	1192	1192	1192	1192
Coarse Agg. (lb)	1887	1887	1887	1887	1887	1887	1887	1887	1887	1887
Air Ent. Agent (ml)	216	225	234	243	261	270	261	270	288	297
Water/Cement Ratio	0.41	0.42	0.39	0.38	0.37	0.37	0.33	0.34	0.32	0.35
Time of Set										
Initial (hrs:min)	9:54	12:00	16:48	14:36	20:12	18:12	23:54	25:24	25:48	26:36
Final (hrs:min)	14:48	17:18	22:09	20:12	26:06	23:36	33:18	32:30	35:24	37:18
Slump (in.)										
Time (min): 0	2 3/4	3 1/4	3 1/4	3 1/4	2 1/4	3	3	3	1 3/4	2 3/4
30	2 1/2	3	3	2 3/4	1 3/4	2 1/2	2 1/4	1 3/4	1 3/4	2 1/4
60	2	2 3/4	2 3/4	2 1/2	1 1/4	2 1/4	2 1/2	2	1 1/2	2
90	1 1/2	2 1/2	2 1/2	2 1/4	3/4	2	2	1	1	1 1/4
120	1 1/2	2	2 1/2	2 1/4	1	1 1/2	1 1/2	1	1	1
Air (%)										
Time (min): 0	5.6	6.6	5.9	7.0	5.9	7.0	5.8	6.8	5.6	6.4
30	4.9	5.0	5.0	5.6	4.6	5.0	4.6	5.1	5.0	4.6
60	4.6	5.0	5.0	5.4	4.4	5.0	4.6	4.4	4.9	4.6
90	4.4	4.6	4.9	5.0	4.5	4.9	4.6	4.4	5.2	4.6
120	4.4	4.6	4.9	5.0	4.5	4.9	4.6	4.6	5.0	4.6
Unit Weight (lb/ft^3)										
Time (min): 0	145	143	145	142	144	142	145	143	145	144
30	147	145	146	146	147	146	147	146	146	147
60	147	145	146	147	148	146	146	147	147	147
90	147	145	147	147	148	146	147	147	147	147
120	147	145	147	147	148	147	147	147	147	147
Temperature (C)										
Time (min): 0	15	14	14	14	14	15	14	14	14	14
30	16	14	15	14	15	15	15	15	14	14
60	16	14	15	14	15	15	14	15	14	14
90	15	14	15	14	15	15	15	15	14	14
120	15	14	15	14	15	15	15	15	14	14
Static Modulus of Elasticity (ksi)	4210	3900	3890	4030	4140	3840	3850	4170	4260	3970
Compressive Strength 28 days (ksi)	5.51	4.85	4.89	4.96	5.70	5.39	4.84	5.48	5.77	5.49

1 lb/yd^3 = 0.593 kg/m^3; 1 ml/yd^3 = 1.31 ml/m^3; 1 in. = 25.4 ml; 1 lb/ft^3 = 16.0 kg/m^3; 1 ksi = 6.89 MPa.

TABLE VII

CONCRETE DATA FOR TASK NO. 2, 70 F (21 C)

Item	Percent Fly Ash 0		20		30		40		50	
Batch	1	2	1	2	1	2	1	2	1	2
Quantities Per Yd^3										
Cement (lb)	564	564	452	452	395	395	338	338	282	282
Fly Ash (lb)	0	0	112	112	169	169	226	226	282	282
Water (lb)	241	241	198	205	203	203	189	203	194	203
Fine Agg. (lb)	1170	1170	1170	1170	1170	1170	1170	1170	1170	1170
Coarse Agg. (lb)	2064	2064	2064	2064	2064	2064	2064	2064	2064	2064
Air Ent. Agent (ml)	225	234	270	288	297	306	324	342	342	351
Water/Cement Ratio	0.43	0.43	0.35	0.36	0.36	0.36	0.34	0.36	0.34	0.36
Time of Set										
Initial (hrs:min)	5:42	6:00	8:54	8:06	10:49	10:00	12:12	13:42	17:00	14:42
Final (hrs:min)	8:00	8:00	11:48	11:24	13:30	13:18	16:30	18:12	21:18	19:54
Slump (in.)										
Time (min): 0	3	2	1 1/4	2	1 3/4	3	2 1/4	3	3 1/4	3
30	1 3/4	1	1	1/2	1 1/2	1 1/2	1	1 1/4	2	1 3/4
60	1 1/4	1	1/2	1/2	3/4	1	3/4	1 1/4	1 3/4	1 1/2
90	1	1	---a	---a	---a	3/4	1/2	3/4	3/4	1
120	---a	1/2	---a	---a	---a	---a	---a	---a	---a	1/2
Air (%)										
Time (min): 0	5.5	6.1	5.8	6.0	5.9	6.8	5.0	6.7	5.8	6.5
30	3.6	4.7	4.2	4.4	4.7	4.4	4.8	5.4	4.4	4.7
60	3.4	4.5	4.1	4.4	4.4	4.3	4.4	4.5	4.1	4.2
90	2.4	4.5	---a	---a	---a	4.2	4.8	4.5	4.1	4.2
120	---a	3.9	---a	---a	---a	---a	---a	---a	---a	3.9
Unit Weight (lb/ft^3)										
Time (min): 0	149	150	151	151	151	149	152	149	148	149
30	153	152	153	153	154	153	152	152	151	152
60	153	152	153	153	154	153	153	153	151	153
90	153	152	---a	---a	---a	154	152	153	152	152
120	---a	153	---a	---a	---a	---a	---a	---a	---a	153
Temperature (C)										
Time (min): 0	22.0	21.0	21.0	21.0	21.0	21.0	20.5	20.0	20.0	20.5
30	21.5	21.0	21.0	21.0	21.0	21.0	20.5	20.0	21.0	21.0
60	21.5	21.5	21.0	21.0	21.0	20.5	20.5	20.0	21.0	20.5
90	20.5	21.0	---a	---a	---a	20.5	20.5	20.5	21.0	20.5
120	---a	21.0	---a	---a	---a	---a	---a	---a	---a	20.5
Static Modulus of Elasticity (ksi)	4850	4720	4800	4630	4600	4420	4440	4280	4130	4150
Compressive Strength 28 days (ksi)	4.96	5.26	6.26	6.33	5.64	5.64	5.63	5.11	4.59	4.41

[a]Test terminated.

1 lb/yd^3 = 0.593 kg/m^3; 1 ml/yd^3 = 1.31 ml/m^3; 1 in. = 25.4 mm; 1 lb/ft^3 = 16.0 kg/m^3; 1 ksi = 6.89 MPa.

TABLE VIII

CONCRETE DATA FOR TASK NO. 2, 90 F (32 C)

Item	Percent Fly Ash									
	0		20		30		40		50	
Batch	1	2	1	2	1	2	1	2	1	2
Quantities Per Yd^3										
Cement (lb)	564	564	452	452	395	395	338	338	282	282
Fly Ash (lb)	0	0	112	112	169	169	226	226	282	282
Water (lb)	222	233	207	200	209	212	203	219	197	203
Fine Agg. (lb)	1192	1192	1192	1192	1192	1192	1192	1192	1192	1192
Coarse Agg. (lb)	1887	1887	1887	1887	1887	1887	1887	1887	1887	1887
Air Ent. Agent (ml)	225	243	288	306	306	324	342	369	351	360
Water/Cement Ratio	0.39	0.42	0.37	0.35	0.37	0.38	0.36	0.39	0.35	0.36
Time of Set										
Initial (hrs:min)	2:39	3:09	3:51	3:38	5:11	4:59	5:48	5:36	5:00	6:39
Final (hrs:min)	4:09	4:23	4:24	5:42	6:56	7:05	7:50	7:11	7:48	10:26
Slump (in.)										
Time (min): 0	2	2 1/4	2	2 1/2	2	2	2 1/2	3	2 1/2	2 1/2
30	1	1 1/2	1 1/2	1 3/4	3/4	3/4	3/4	2	1/4	3/4
60	1/2	3/4	1	1	1/4	1/2	1/2	1	1/2	1/2
90	1/2	1/2	3/4	1 1/2	---[a]	---[a]	---[a]	1	---[a]	---[a]
Air (%)										
Time (min): 0	5.0	6.0	5.0	6.0	5.5	6.0	5.7	6.4	5.7	6.0
30	4.3	4.5	4.5	4.8	4.0	4.5	4.0	4.8	4.2	3.8
60	4.2	4.2	4.5	4.3	4.0	4.5	4.2	4.8	4.2	4.0
90	4.2	4.5	4.5	4.3	---[a]	---[a]	---[a]	4.8	---[a]	---[a]
Unit Weight (lb/ft^3)										
Time (min): 0	146	145	146	145	146	145	145	144	145	145
30	147	147	147	146	148	148	148	146	147	147
60	148	147	147	147	148	148	147	146	147	147
90	148	146	147	147	---[a]	---[a]	---[a]	146	---[a]	---[a]
Temperature (C)										
Time (min): 0	35	34	33	33	33	33	33	34	33	33
30	34	34	33	34	33	34	33	34	34	33
60	34	34	33	34	33	34	33	34	34	33
90	34	33	33	34	---[a]	---[a]	---[a]	34	---[a]	---[a]
Static Modulus of Elasticity (ksi)	4040	4000	4290	3890	3930	4290	3880	3590	3800	3814
Compressive Strength 28 days (ksi)	5.02	4.99	5.65	4.75	5.27	5.57	4.78	4.25	4.71	4.60

[a]Test terminated.

1 lb/yd^3 = 0.593 kg/m^3; 1 ml/yd^3 = 1.31 ml/m^3; 1 in. = 25.4 mm;
1 lb/ft^3 = 16.0 kg/m^3; 1 ksi = 6.89 MPa.

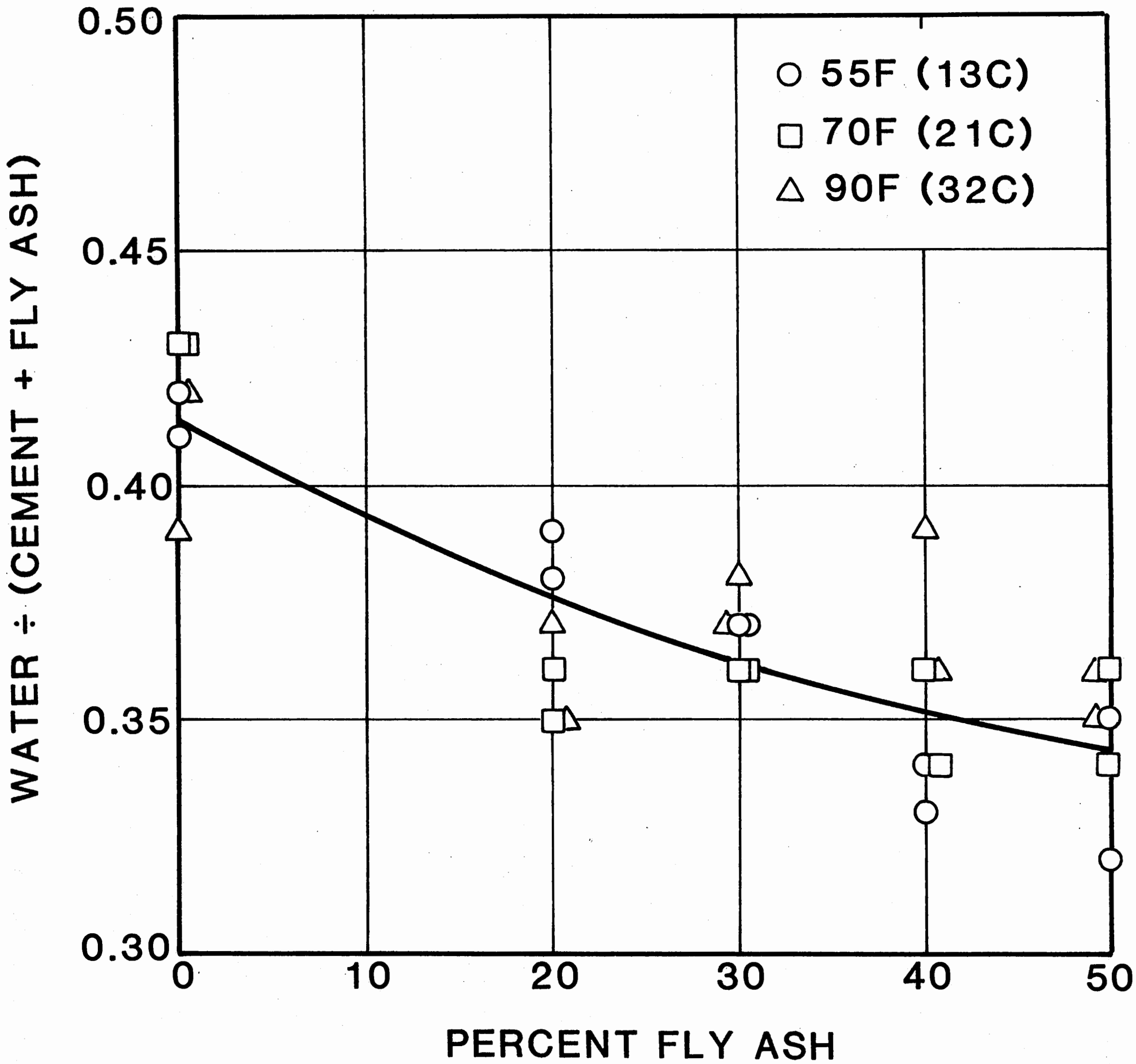

Figure 10. Influence of Fly Ash on Mix Water

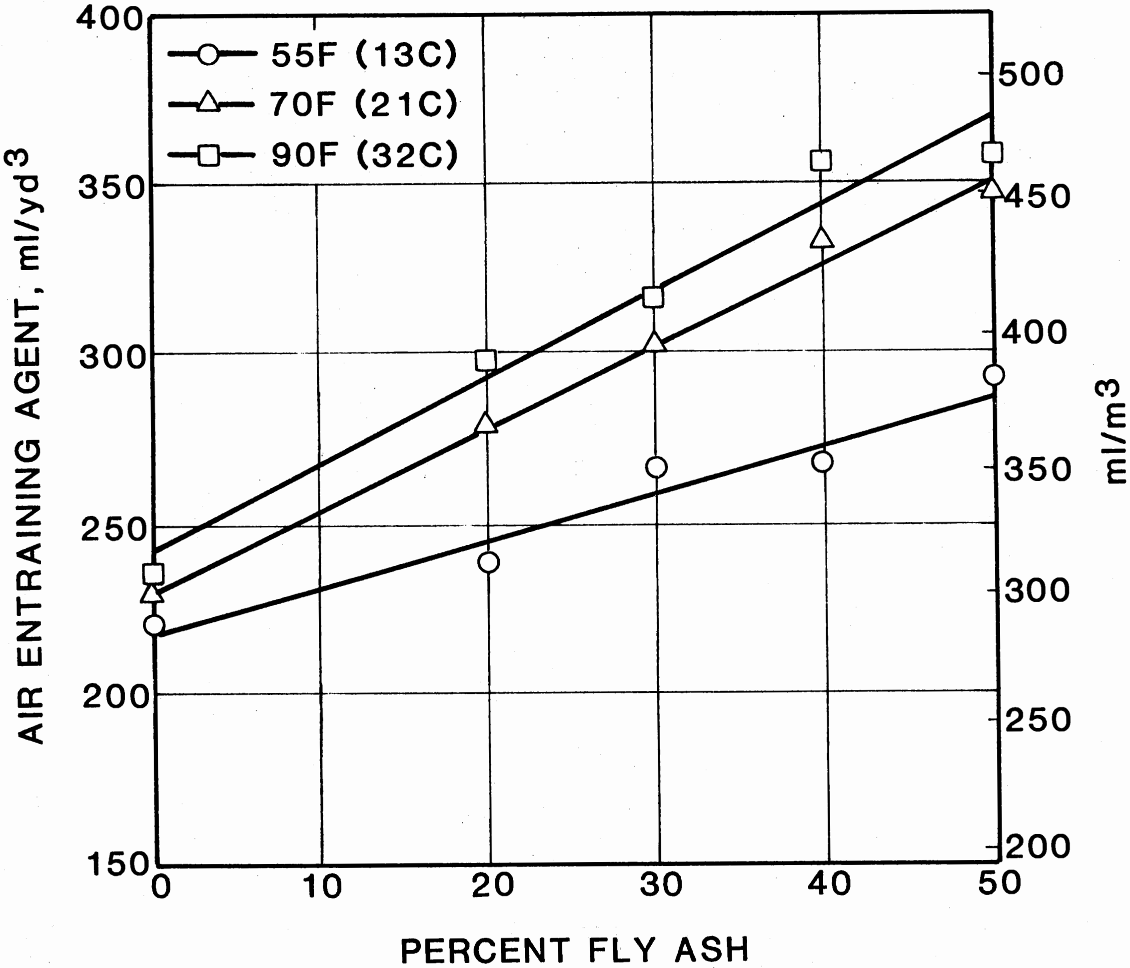

Figure 11. Influence of Percent Fly Ash and Temperature on Air Entraining Agent Demand

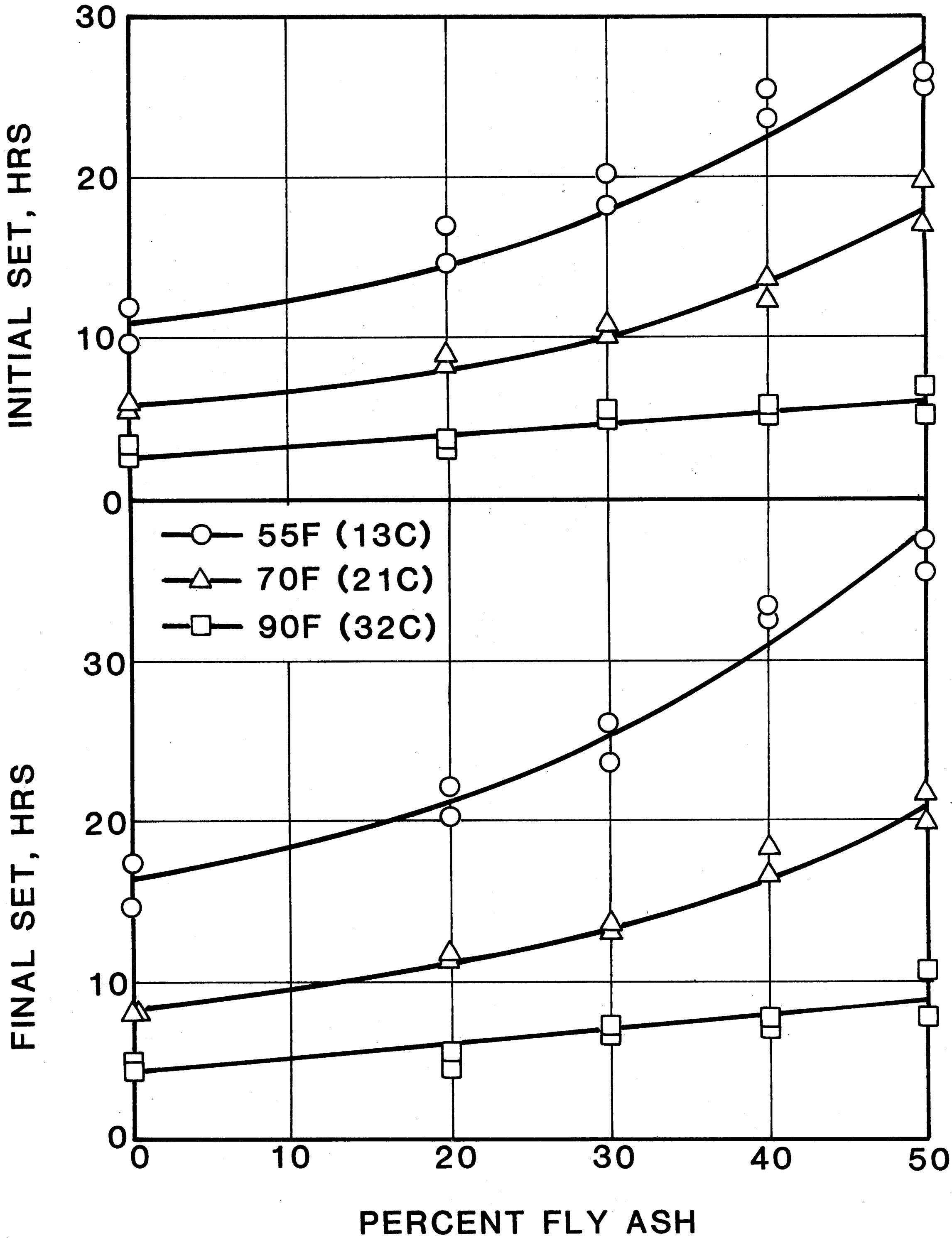

Figure 12. Influence of Percent Fly Ash and Temperature on Time of Set

initial and final time of set were strongly retarded; the times of set for mixes with 50 percent fly ash were approximately double those for mixes without fly ash. Prior to removal of molds, cylinders were maintained at the mixing temperature; thereafter, cylinders used to establish the compressive strength and modulus of elasticity were subjected to standard curing conditions. Specimens made with fly ash usually had higher compressive strength at 28 days than the control specimen; however, specimens with 50 percent fly ash were about the same strength or slightly weaker than control cylinders. Data regarding the hardened air void system are given in Tables IX, X, and XI.

6.3.3 Influence of Extended Agitation

In Figure 13, the stiffening, or loss of slump, during agitation is shown. When the temperature was 55 F (13 C), the rate of stiffening was approximately constant during 120 minutes of agitation. At higher temperatures the rate of slump loss during the first 30 minutes was usually greater than the remainder of the agitation period. The influence of fly ash on stiffening was very limited. During agitation the temperature of all batches remained essentially constant.

6.4 Discussion of Results

6.4.1 Mix Proportions

Overall, the replacement of portland cement with an equal weight of fly ash was found to require modest adjustments in the quantities of mix water and AEA. This suggests that fly ash can be used successfully in the field without greater difficulty than would be expected with other common admixtures. However, all data were developed using a single

TABLE IX

AIR VOID DATA FROM MICROSCOPIC EXAMINATION, TASK NO. 2, 55 F (13 C)

Item	Percent Fly Ash									
	0		20		30		40		50	
Batch	1	2	1	2	1	2	1	2	1	2
Air Content (%)										
Time (min): 0		6.8	7.2	8.5	8.7	10.2	8.7	8.2	4.7	4.9
30		3.5	6.8	8.5	6.4	5.5	6.4	7.4	5.1	4.7
60		4.7	7.1	6.6	7.4	4.9	9.3	7.2	5.6	4.0
90		4.8	6.6	8.6	8.6	3.7	9.2	7.2	4.2	4.2
120		5.1	5.9	6.1	6.9	4.7	11.0	7.3	6.9	4.1
Specific Surface (in.^{2}/in.^{3})										
Time (min): 0	290	520	360	390	410	550	320	440	480	410
30	380	550	330	320	410	430	360	270	520	340
60	450	620	380	410	370	410	230	370	430	370
90	410	460	350	350	290	590	280	380	620	400
120	290	630	340	350	370	390	260	350	440	390
Spacing Factor (in.)										
Time (min): 0	0.012	0.007	0.009	0.007	0.007	0.008	0.008	0.006	0.010	0.011
30	0.012	0.010	0.011	0.009	0.009	0.010	0.010	0.012	0.009	0.014
60	0.012	0.008	0.009	0.009	0.009	0.011	0.011	0.009	0.010	0.013
90	0.012	0.010	0.011	0.008	0.010	0.009	0.009	0.009	0.008	0.012
120	0.017	0.007	0.012	0.011	0.010	0.012	0.008	0.009	0.008	0.013

1 in.^{2}/in.^{3} = 0.0394 mm^2/mm^3; 1 in. = 25.4 mm.

TABLE X

AIR VOID DATA FROM MICROSCOPIC EXAMINATION, TASK NO. 2, 70 F (21 C)

Item	Percent Fly Ash									
	0		20		30		40		50	
Batch	1	2	1	2	1	2	1	2	1	2
Air Content (%)										
Time (min): 0	3.6	7.4	3.7	4.7	3.8	6.9	5.5	3.3	8.0	3.8
30	---	5.2	2.8	2.9	3.4	5.6	7.0	2.9	10.1	3.1
60	3.2	5.4	2.7	2.5	2.9	7.5	5.5	4.0	6.5	3.3
90	3.2	5.5	---	---	---	6.1	6.8	3.4	6.5	3.5
120	---	8.6	---	---	---	---	---	---	---	2.7
Specific Surface ($in.^2/in.^3$)										
Time (min): 0	380	320	410	440	510	490	420	570	310	520
30	370	290	360	280	350	340	270	440	320	430
60	410	290	460	480	380	270	380	450	330	270
90	260	300	---	---	---	370	330	420	340	330
120	---	190	---	---	---	---	---	---	---	440
Spacing Factor (in.)										
Time (min): 0	0.014	0.010	0.012	0.010	0.010	0.007	0.010	0.009	0.009	0.010
30	0.016	0.016	0.016	0.020	0.015	0.012	0.012	0.013	0.007	0.013
60	0.014	0.016	0.013	0.013	0.015	0.012	0.011	0.011	0.011	0.020
90	0.022	0.015	---	---	---	0.010	0.010	0.013	0.011	0.016
120	---	0.015	---	---	---	---	---	---	---	0.014

$1\ in.^2/in.^3 = 0.0394\ mm^2/mm^3$; 1 in. = 25.4 mm.

TABLE XI

AIR VOID DATA FROM MICROSCOPIC EXAMINATION, TASK NO. 2, 90 F (32 C)

Item	Percent Fly Ash									
	0		20		30		40		50	
Batch	1	2	1	2	1	2	1	2	1	2
Air Content (%)										
Time (min): 0	8.3	9.1	3.6	7.9	3.1	10.9	3.8	9.1	7.3	4.8
30	7.7	10.0	3.4	5.3	3.8	7.7	4.1	8.8	6.0	4.0
60	7.9	7.4	4.4	7.0	3.7	9.0	2.9	8.1	6.8	4.0
90	8.3	10.3	3.5	8.1	---	---	---	8.5	---	---
120	---	---	---	---	---	---	---	---	---	---
Specific Surface (in.^{2}/in.^{3})										
Time (min): 0	300	290	390	260	480	250	330	350	300	450
30	310	270	480	330	390	280	330	330	330	580
60	300	310	350	250	320	330	500	350	380	570
90	260	220	380	290	---	---	---	340	---	---
120	---	---	---	---	---	---	---	---	---	---
Spacing Factor (in.)										
Time (min): 0	0.010	0.009	0.014	0.012	0.012	0.009	0.016	0.008	0.011	0.010
30	0.011	0.009	0.011	0.013	0.013	0.011	0.015	0.009	0.012	0.018
60	0.010	0.011	0.014	0.014	0.017	0.008	0.012	0.009	0.009	0.015
90	0.012	0.011	0.014	0.010	---	---	---	0.009	---	---
120	---	---	---	---	---	---	---	---	---	---

1 in.^{2}/in.^{3} = 0.0394 mm^2/mm^3; 1 in. = 25.4 mm.

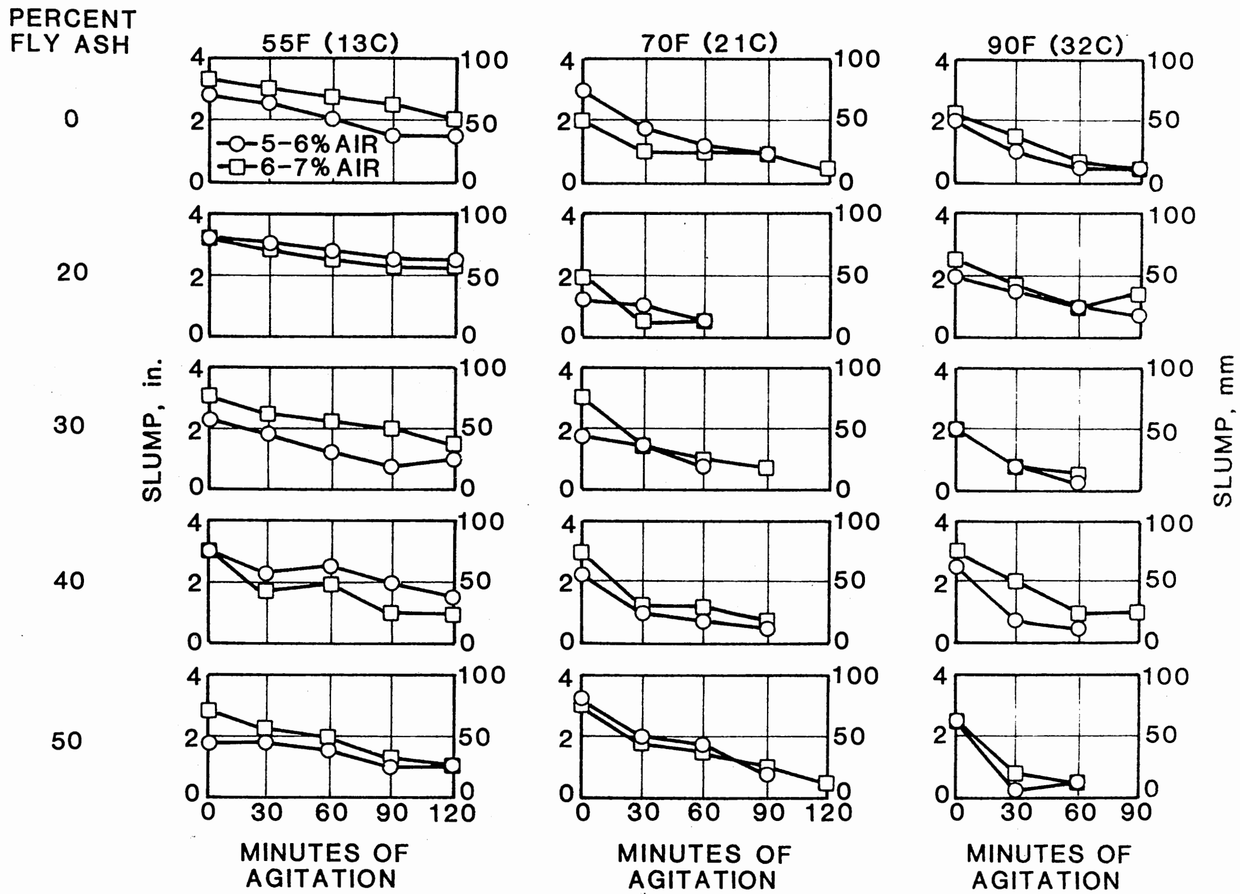

Figure 13. Influence of Fly Ash, Temperature, and Agitation on Loss of Slump

shipment of portland cement and fly ash. Therefore, the influence of variable materials on mix proportions was not established.

As discussed above, a relatively high alkali content in the mix water from portland cement or fly ash can cause a given dose of neutralized vinsol resin to entrain more air. However, laboratory analyses of the portland cement and fly ash used in this study indicate that both materials had negligible water soluble alkalies. Therefore, it is believed that the AEA demand increased with fly ash percentage in this study because of the chemical characteristics of the materials used. If the fly ash and portland cement had contained higher, more typical alkali percentages, the AEA demand would have been smaller--probably reversing the trend obtained in this investigation.

The data regarding the w/c ratio at various percentages of fly ash and mix temperatures have some unavoidable scatter--some of which was related to laboratory procedures and apparatus. Simultaneous adjustments in AEA dosage as well as mix water--which have interactive influences--plus a tolerance in slump and air content were partially responsible for fluctuations. Some aggregate may have been used for casting before reaching the air dry condition which would have produced variations in slump or mix water. In addition, the mix proved to be relatively stiff for a small mixer charged to capacity. It is believed that fly ash similar to that used in the present study will permit a significant reduction in mix water. However, a precise relationship between the reduction and the percentage of fly ash and the influence of mix temperature was not possible with constraints and procedures associated with the experimental program. However, the influence of temperature on mix proportions appeared to be relatively minor. Consequently, when fly ash is used in field application, fluctuating temperatures will probably not require significant mix adjustments.

6.4.2 Concrete Properties

In order for fly ash to be used for general purpose construction applications, the resulting concrete must possess mechanical properties which are similar to those of conventional concrete. Data obtained here indicate that fly ash can be used to replace up to 50 percent of the portland cement without serious impact on the compressive strength at 28 days. As shown in Figure 14, fly ash concrete with 20 to 40 percent replacement was usually stronger than the control mix; this result was largely related to the reduction in mix water made possible with the use of fly ash. If the ratio of water to cement plus fly ash had been held constant and the proportions of cement, fly ash, and aggregated adjusted to maintain constant slump, fly ash would probably result in reduced strength. The ACI Building Code (40) expresses the modulus of elasticity of concrete as

$$E_c = 33\, w_c^{1.5} \sqrt{f'_c}$$

where

E_c = modulus of elasticity, psi;

w_c = unit weight of concrete, pcf; and

f'_c = compressive strength of concrete, psi.

In Figure 15, $E_c \div (w_c^{1.5} \sqrt{f'_c})$ is plotted against percent fly ash. It can be seen that the constant of proportionality was approximately equal to 33 in this study and that the constant was independent of percent fly ash. Since the unit weight was approximately constant, it was concluded that

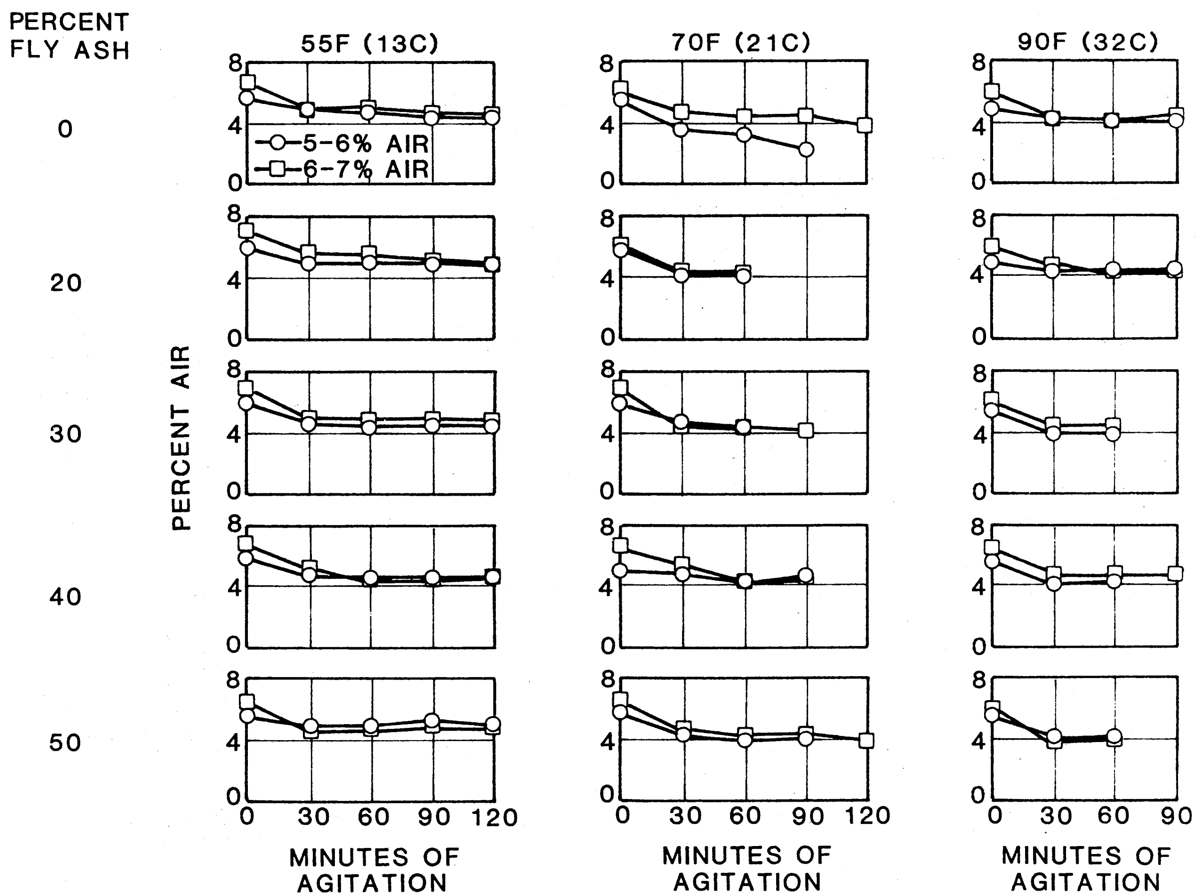

Figure 14. Influence of Fly Ash, Temperature, and Agitation on Air Loss

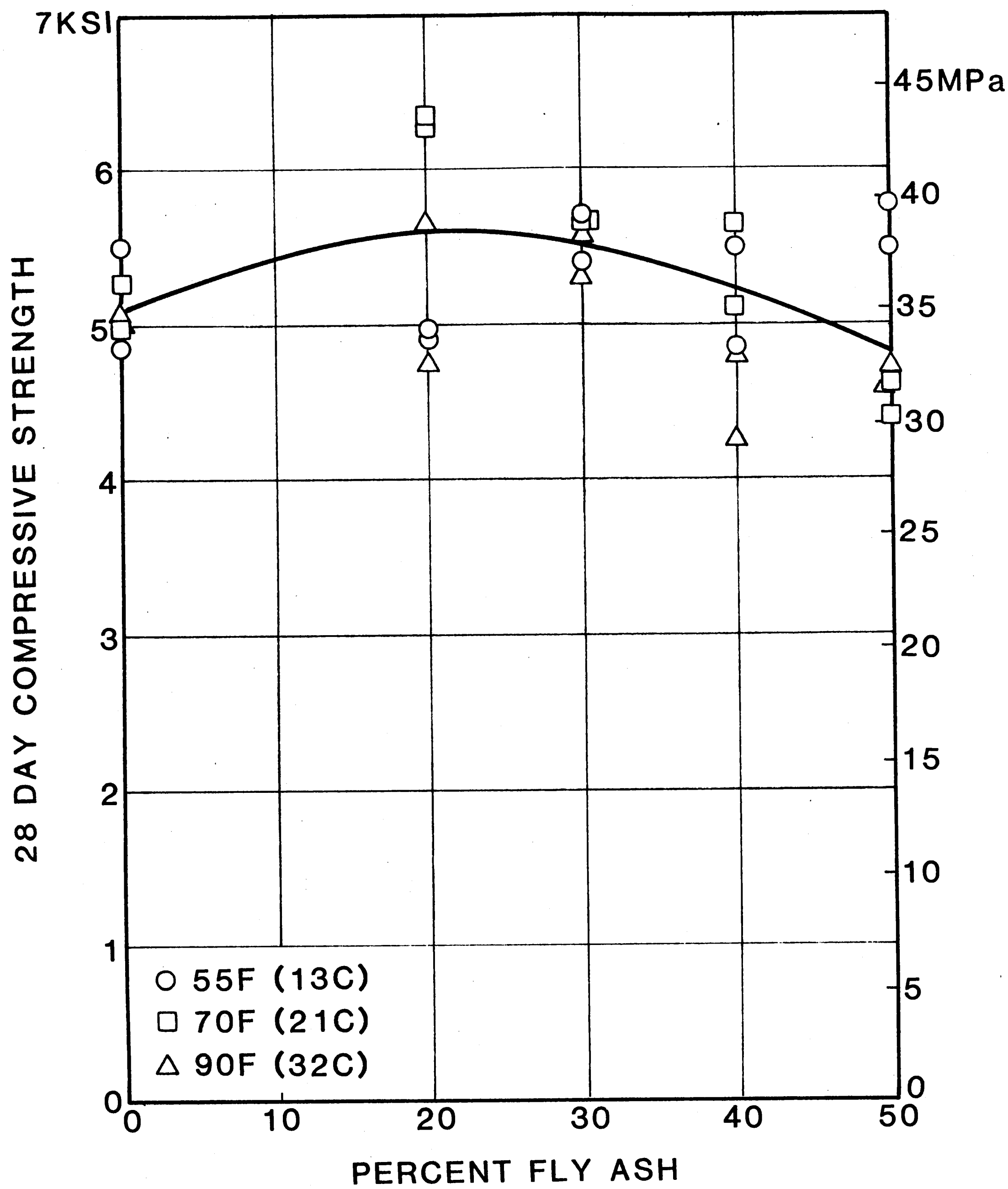

Figure 15. Influence of Fly Ash on Compressive Strength

the modulus of elasticity of all concrete was principally related to compressive strength; any influence resulting from fly ash was minor.

Probably the most pronounced influence of fly ash was on the time of set. Data obtained at 55 F (13 C) suggest that the rate of retarding action increases with fly ash percentage (see Figure 12). This curvilinear relationship was not noticed at 90 F (32 C). The influence of fly ash percentage on strength obtained at various curing temperatures was not investigated. Data obtained at 70 F (23 C) suggest that the retarding influence of fly ash is limited to the first day or two after casting, and that after this period plain concrete and fly ash gain strenth with additional curing at a similar rate. When construction procedures require a minimum strength at an early age--e.g., for form removal--or require later strength to be estimated from strength at early ages, the influence of fly ash should be carefully investigated.

Hardened air void data taken during this phase of the study and the durability related effort required several hundred hours of microscopic examination. To complete this effort within the time span available, it was necessary to use several microscopists. By the time readings were essentially complete, analysis of data revealed obvious discrepancies in measurements taken by various individuals. In an attempt to improve the accuracy of data, many samples were reexamined once or even twice. However, these efforts were only partially successful. The microscope readings, inherently subjective, were found to be sensitive to the magnifying power used by the various individuals. Based on the quantity of data, the decision was made to compute air void parameters using a paste content based on mix proportions. This approach would be satisfactory if a cross section with representative percentage of paste, fine aggregate, coarse aggregate, and air were examined; in a few instances, a cursory examination suggested the percentage of coarse aggregate was quite variable.

Further refinements in experimental techniques did not seem justified at the completion of measurements. All freeze-thaw specimens had performed well regardless of fly ash percentages--a fact that suggests an acceptable air void system was present. The low alkali content found in the portland cement and fly ash would have promoted the entrainment of small, stable bubbles, thus minimizing the opportunity to detect trends between the quality of the air void system and other test parameters. Consequently, air void data presented in Tables X, XI, and XII should be considered as qualitative.

6.4.3 Influence of Extended Agitation

As can be seen in Figure 16, the percentage fly ash and probably the temperature had little influence on air loss during agitation. The mixes with a higher initial air content (6 to 7%) often had a slightly greater air loss during the first 30 minutes of agitation than mixes with a lower air content (5 to 6%). After the first minute of agitation, the subsequent air loss did not seem to be related to the initial air content.

It is well known that slump and air content are related; therefore, any tendency for mixes with a higher air content to lose more air during the first 30 minutes of agitation should be reflected in slump data taken during this period.

Noting the retarding action caused by fly ash on time of set, some engineers suggest that fly ash concrete may be ideally suited to hot

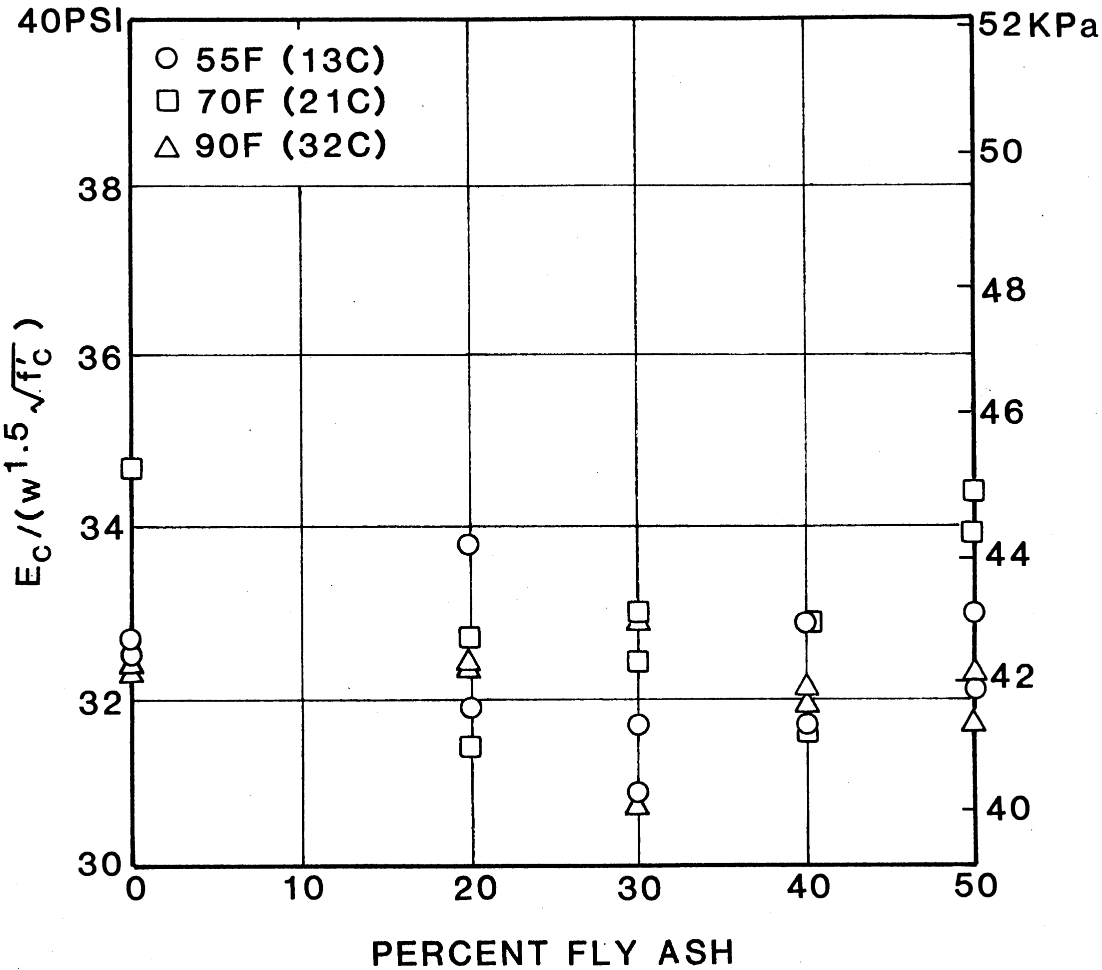

Figure 16. Influence of Fly Ash on Modulus of Elasticity

weather applications. Data presented in Figure 13 suggest that at a given temperature, fly ash will not retard stiffening of the plastic concrete; in fact, the slump loss may actually increase with fly ash percentage. Therefore, from a workability standpoint fly ash appears to slightly accelerate stiffening. If this behavior is evidenced in the field, workmen will be tempted to retemper the concrete with adverse consequences to the properties of the hardened concrete. However, if mixes containing fly ash are properly designed and adequate field supervision is exercised, problems arising from premature stiffening caused by fly ash should be minimal.

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